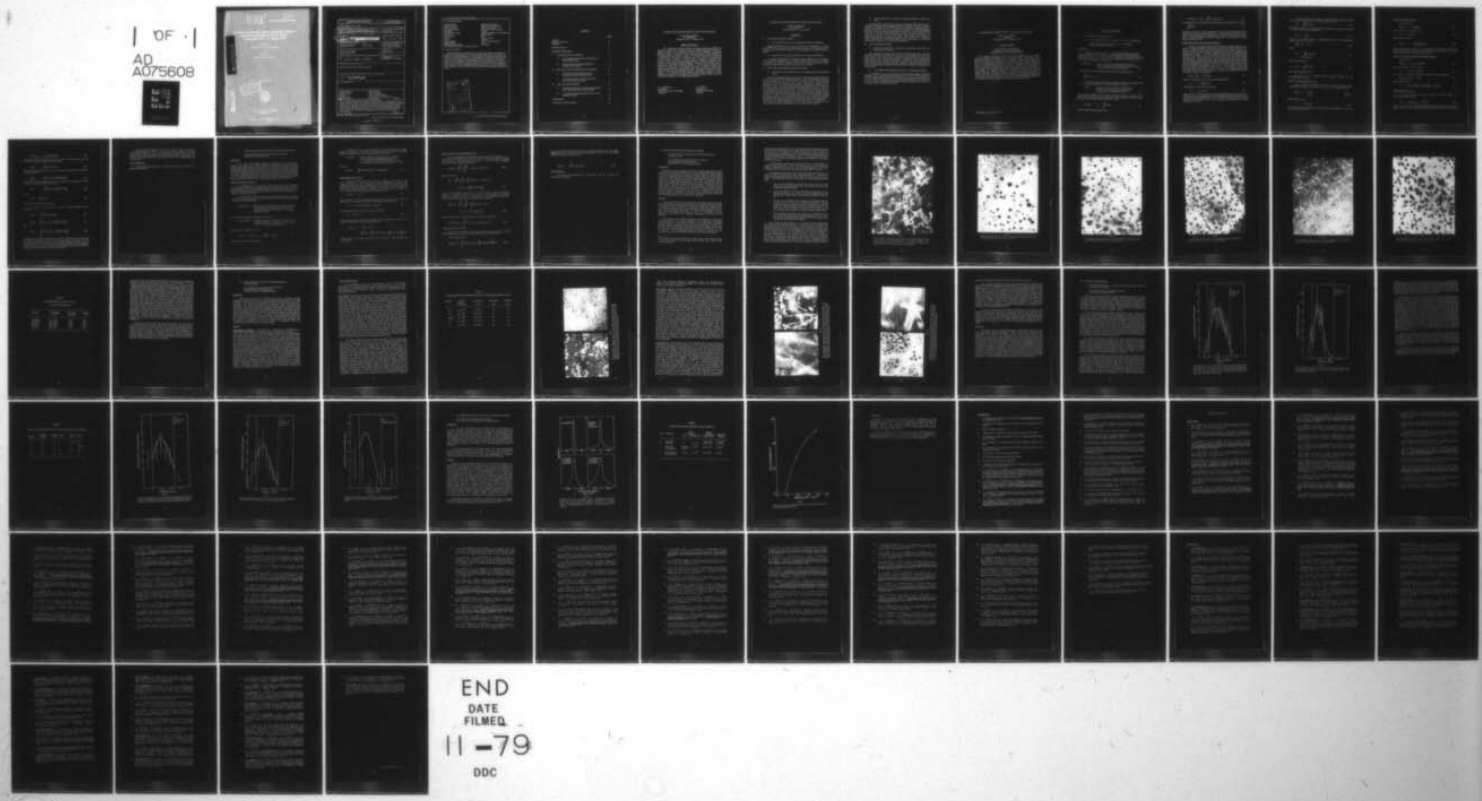
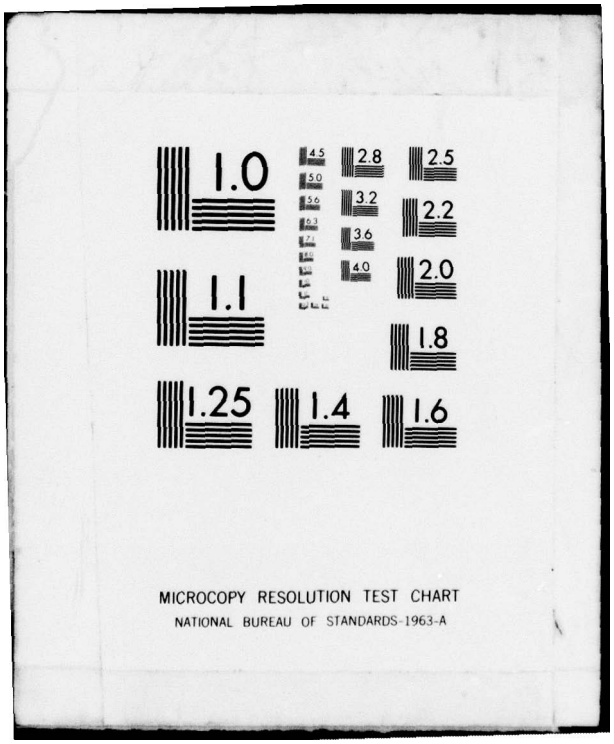
AD-A075 608 NAVAL RESEARCH LAB WASHINGTON DC F/G 9/2
COOPERATIVE RADIATION EFFECTS SIMULATION PROGRAM.(U)
OCT 79 F A SMIDT, L A BEACH
UNCLASSIFIED NRL-MR-4080 NL



END
DATE FILMED
11-79
DDC


1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0
5.6
6.3
7.1
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: NRL Memorandum Report 4080
2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle): COOPERATIVE RADIATION EFFECTS SIMULATION PROGRAM, ~~ANNUAL PROGRESS REPORT FOR THE PERIOD 1 SEPTEMBER 1977 – 31 AUGUST 1978~~ AD A074040
5. TYPE OF REPORT & PERIOD COVERED: Progress Report 1 September 1977 31 August 1978
6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s): F. A. Smidt, Jr. [redacted] L. A. Beach [redacted] Division
8. CONTRACT OR GRANT NUMBER(s): 4 Oct 79

9. PERFORMING ORGANIZATION NAME AND ADDRESS: Naval Research Laboratory, Washington, DC 20375
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: NRL Problems M01-22, M01-27, H01-83, H01-70 and H01-67

11. CONTROLLING OFFICE NAME AND ADDRESS: Office of Naval Research, Arlington, Virginia 22217
12. REPORT DATE: October 4, 1979
13. NUMBER OF PAGES: 71

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): NRL-MR-4080
15. SECURITY CLASS. (of this report): UNCLASSIFIED
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

Annual progress rept. 1 Sep 77-31 Aug 78,

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Computer modeling	Energy deposition
Deuterium diffusion	Heavy ion irradiation
Dislocations	Heavy ion radiation damage
Dislocation loops	He, D-elastic scattering measurements
Electron microscopy	Helium diffusion

(Continues)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The Cooperative Radiation Effects Simulation Program (CORES) is a collaborative effort of the Material Science and Technology and Radiation Technology Divisions of NRL Material and Radiation Science and Technology Area. The goal of the research is to provide the theoretical and experimental bases for understanding the mechanisms of nuclear radiation damage of metals, as well as a theoretical insight into energy deposition processes. In this the Van de Graaff and Cyclotron are used to simulate rapidly the radiation damage produced over long periods in reactor neutron environments.

(Continues)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

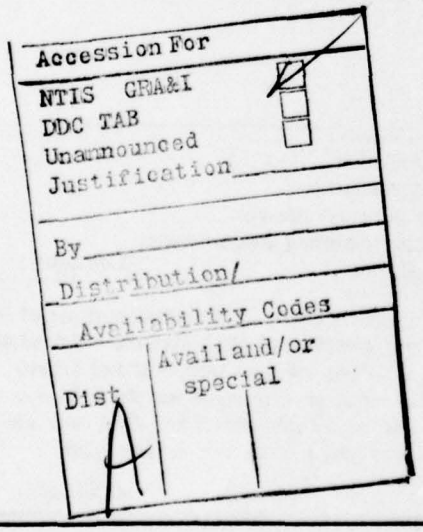
251 950

19. Key Words (Continued)

Hydrogen diffusion
Interstitials in metals
Light ion irradiations
Metal radiation damage
Molybdenum
Neutron radiation damage
Nickel alloys
Nickel ion beams
Niobium
Nb-1%Zr
Primary knockons
Radiation damage
Radiation damage simulation
X-ray diffraction measurements of dislocation density
Radiation-induced defects
Radiation-induced displacements
Refractory metal alloys
Simulation of neutron irradiations
Swelling
Temperature dependence of void formation
Transport theory
TZM
Vacancies in metals
Vanadium
Van de Graaff bombardments
Voids
Void growth

20. Abstract (Continued)

Progress for the period, 1 September 1977 to 31 August 1978, includes: (1) development of a method for calculating energy deposition profiles from range distributions, (2) development of a method to estimate energy deposition in ion bombardments which incorporate transport of energy downstream by primary knockon atoms, (3) an investigation of the influence of 1 atomic percent Al, Mo, Si and Ti, respectively, to the swelling behavior of binary nickel alloys under neutron irradiation; (4) an investigation of swelling in refractory metals and alloys (Mo, Nb, V, TZM, Nb-1% Zr and V-20% Ti) at 625°C for fast neutron fluences to 5.4 x 10^{22} n/cm^2; (5) an investigation of deuterium trapping in radiation damaged aluminum and stainless steel using elastic scattering techniques to measure the increase in dislocation density produced by radiation damage in copper single crystals.



CONTENT

COOPERATIVE RADIATION EFFECTS SIMULATION PROGRAM

Annual Progress Report
for the period
1 September 1977 - 31 August 1978

Program Description

The Cooperative Radiation Effects Simulation Program (CORES) was initiated voluntarily by five Branches from the Engineering Materials (now the Material Science and Technology Division) and the Radiation Technology Division of NRL on the basis of their common interests in the problems of simulating radiation damage in metals. The program promotes the exchange of information, discussion of problems, and the pursuit of collaborative research efforts. Annually a written report is prepared containing those portions of the work of the participating Branches which are judged to be of interest to the damage simulation problem. The major portion of the work is sponsored by the Office of Naval Research. Since research findings which apply to the objectives of one sponsor may also be of interest to others, the overall progress related to damage simulation is included in the written report. Several of the participating Branches have independent programs on other aspects of the radiation damage problem; when results obtained in these programs are judged to be of interest to CORES participants they may also be included, informally, in the CORES program review.

F. A. SMIDT, JR.
Coordinator
Material Science & Technology
Division

L. A. BEACH
Coordinator
Radiation Technology
Division

COOPERATIVE RADIATION EFFECTS SIMULATION PROGRAM

Annual Progress Report
for the Period
1 September 1977 - 21 August 1978

SUMMARY

I. RADIATION DAMAGE THEORY

A. Use of Range Distribution to Approximate Energy Distributions

Range distributions can be used to estimate the distribution in energy which develops in an ion beam as it penetrates a target. Several variants of this approach are discussed and applied to the calculation of energy deposition profiles.

B. Approximation for Energy Deposition in Ion Beam Bombardment

A method is developed for estimating energy deposition in ion bombardment. By making extensive use of a table of range versus energy, it is possible to estimate the energy transport effects due to primary knock-on atoms depositing energy downstream from the sites of their creation.

II. HEAVY ION AND NEUTRON DAMAGE STUDIES

A. The Effect of Alloy Additions on the Swelling of Neutron Irradiated Nickel

The void and dislocation structures in pure nickel and the binary alloys Ni-1 at.% Al, Ni-1 at.% Mo, Ni-1 at.% Si, and Ni-1 at.% Ti were examined following neutron irradiation to 2.2×10^{22} n/cm^2 ($E > 0.1$ MeV) at 455°C. The dislocation structures of all the materials were similar, consisting of tangles of line dislocations, many of which intersected voids. Comparing the void formation of the alloys to that in the pure nickel, the following observations were made: the Al addition did not significantly affect the void formation, except to make it more homogeneous and to narrow the size distribution; the Mo and Ti both increased the swelling by about a factor of two, with the Mo increasing the void number density and the Ti increasing the void size; the Si decreased the swelling by about a factor of ten, by reducing the void size. These results differ significantly from those of an earlier ion irradiation study of the same alloys, in which all of these alloying elements reduced or eliminated the void formation. The reason for these differences is most likely related to different void nucleation mechanisms being important in the two types of irradiation.

B. The Microstructure of Neutron Irradiated Refractory Metals and Alloys

The refractory metals Mo, Nb, and V and the alloys TZM, Nb-1%Zr and V-20%Ti were examined by transmission electron microscopy following irradiation at 650°C to fluences of 5.4×10^{22} n/cm^2, E>0.1 MeV (all materials except V-20%Ti) and 8.4×10^{22} n/cm^2, E>0.1 MeV (Mo and V-20% Ti). Voids representing significant volume swelling were observed in the Mo (2.3 - 3.0%), TZM (4.0%), Nb (1.5%) and V (3.6%). Some precipitation occurred during irradiation in all materials except the Mo and V. The results indicate that void swelling can probably be controlled at moderate levels at this temperature in refractory alloys. Degradation of mechanical properties due to precipitation of interstitial impurities may, however, be a more serious problem.

III. LIGHT ION BEAM STUDIES

A. Deuterium Retention in Aluminum and Stainless Steel With and Without Helium Loading

Thin samples of aluminum (1.2 mils) and stainless steel (0.6 mils) were implanted with deuterium both with and without prior implantations of helium. These samples were then profiled to determine concentrations of helium and deuterium by elastic scattering techniques. Analysis of these measurements show deuterium was retained in aluminum foils both with and without previous helium implantations but deuterium was retained in stainless steel only with prior helium loading indicating enhanced deuterium retention with predamage in stainless steel.

B. X-ray Diffraction Measurements of Low-Level Radiation Damage

X-ray diffraction gives a quantitative measure of early stages of radiation damage in metals. Alpha-particle irradiations of 2×10^{-2}, 4×10^{-2}, and 6×10^{-2} C/cm^2 in copper single crystals show an apparent threshold of little damage up to 2×10^{-2} C/cm^2 and then a nearly linear increase of dislocations up to 6×10^{-2} C/cm^2. Preliminary experiments with polycrystalline copper, not discussed in this report, seem to show similar results.

COOPERATIVE RADIATION EFFECTS SIMULATION PROGRAM

Annual Progress Report
for the Period
1 September 1977 - 21 August 1978

INTRODUCTION

F. A. Smidt, Jr., Coordinator,
Thermostructural Materials Branch
Material Science & Technology Division

This report summarizes annual research accomplishments of the interdivisional cooperative program now in its eighth year. The goal of this program has been to use ion simulation techniques to increase the understanding of neutron damage of materials for advanced nuclear systems. Light and heavy ion bombardment techniques are used to represent neutron damage in order to accelerate research and to permit an evaluation of critical parameters which might not be feasible using nuclear reactors as test facilities. In this program the techniques applied have advanced along with our growing understanding of radiation damage of materials. To complement the ion damage simulation are other programs such as theoretical evaluations of atomic collisions, computation of energy deposition, and parallel experiments using nuclear reactors. The productivity of the CORES Program is illustrated by a full list of technical papers and presentations in the last section.

Note: Manuscript submitted July 12, 1979

RESEARCH PROGRESS

I. RADIATION DAMAGE ANALYSIS

A. Use of Range Distributions to Approximate Energy Distributions

(Irwin Manning, Radiation-Matter Interaction Branch,
Radiation Technology Division)

Introduction

Consider a uniform ion-beam of energy E_B bombarding an amorphous - target in slab geometry, with the beam parallel to the x-axis and the target surface located at x = 0. We are often interested in the single-particle flux density $\phi(e,x)$ which gives the distribution in energy which develops in the ion beam when it penetrates to a distance x:

$\phi(E,x)\,dE$ = number of beam atoms with energy dE about E which cross, per unit bombarding flux per unit time, a perpendicular unit area at the depth x. (1)

According to this definition, ϕ is normalized to unit bombarding flux:

$$\int_0^\infty \phi(E,0)\,dE = 1. \tag{2}$$

Estimates of this flux density are difficult to obtain, but estimates are much more readily available for the range distribution $f(x, E_B)$,

$f(x)\,dx$ = number of beam atoms per unit perpendicular area per unit bombarding flux per unit time coming to rest at the depth dx about x. (3)

For example, in addition to this range distribution, reference 1 provides for a large variety of beam-target combinations, tables, giving as a function of beam energy, the total range $R(E_B)$, the projected range

$$R_p(E_B) = \langle x \rangle = \int_0^\infty f(x)\,dx, \tag{4}$$

and the range straggling $\alpha(E_B)$, where

$$\alpha^2(E_B) = \langle (x - \bar{x})^2 \rangle = \int_0^\infty (x - R_p)^2 f(x)\, dx. \tag{5}$$

According to the above definition, the range distribution is normalized to unity:

$$\int_0^\infty f(x)dx = 1. \tag{6}$$

This paper concerns a class of methods for using the range distribution f(x) to approximate the energy distribution $\phi(E, x)$. Usually one will utilize the estimate as the integrand inside an integral, which will tend to smooth out errors in $\phi(E, x)$. Section VI below discusses the employment of this estimate to obtain energy deposition profiles.

Energy Distribution from the Range Distribution

We ignore the angular spread which develop in the penetrating beam as it comes to a stop, assuming that the particle velocities are always parallel to the x-axis. Consider the flux of particles $f(x_2, dx_2)$ which will stop at dx_2 about x_2. We make a model in which there are no range fluctuations (in the ordinary sense) among beam particles. In reality, different beam particles undergo different fluctuations in range, but on the average the beam obeys the range-stopping function $R_p(E)$. These fluctuations are removed in our model, and instead, fluctuations are introduced into the model by assigning different range-stopping functions, $\tilde{R}_p(E, x_2)$ to different beam atoms, picked in such a way that the model has the range distribution $f(x_2)$. For the above flux of atoms which will stop in dx_2 about x_2, consider their energy at some $x_1 < x_2$. The fluctuations in our model are such that all of these atoms, when at $x = x_1$, lie within a small energy interval dE, about the energy E_1. There is a one-to-one correspondence between those beam atoms which have energy E_1 at x equal to x_1 and those atoms which will stop at x equal to x_2. We have

$$\phi(E_1, x_1)\, dE_1 = f(x_2)\, dx_2, \tag{7}$$

where E_1 is determined by x_1 and x_2 (and, implicitly, E_B):

$$x_2 = x_1 + R_p(E_1, x_2) \tag{8}$$

which gives E_1 as a function of x_1 and x_2:

$$E_1 = E_1(x_1, x_2). \tag{9}$$

Once a specific model giving the altered range-stopping function $R_p(E, x_2)$ is chosen, $E_1(x_1, x_2)$ is determined by equation (8) and equation (7) then gives an estimate of the energy distribution. For a well-behaved function $E_1(x_1, x_2)$, this estimate is exact in the limit $x_1 \to x_2$, so we expect this estimate to be a good one for $x_2 - x_1$ "small".

One easily verifies that the above estimate (7) obeys an identity satisfied by the true energy distribution. Consider the particle current

$$\vec{j}(\vec{r}) = \int_0^\infty \vec{\phi}(E, \vec{r})\, dE, \tag{10}$$

where $\vec{\phi}$ is the reactor flux corrsponding to scalan flux (1). Gauss' law expresses the conservation of beam particles as

$$\text{div}\, \vec{j} = -\dot{\rho}(r), \tag{11}$$

where ρ is the volume density of stopping particles. For our slab geometry, equations (10) and (11) become

$$\partial/\partial x \quad j(x) = -f(x) \tag{12}$$

where

$$j(x_1) = \int_{\text{all allowed } E_1} dE_1\, \phi(x_1, x) \tag{13}$$

The estimate (4) gives

$$j(x_1) = \int_0^\infty dx_2\, f(x_2), \tag{14}$$

which obeys the identity (12).

We now go on to consider specific models for $\tilde{R}_p(E, x_2)$ and, correspondingly, $E_1(x_1, x_2)$.

Case A: No Fluctuations for $x > x_1$

Here we assume that different beam particles have different range-stopping functions $\tilde{R}_p(E_1, x_2)$ only for $x < x_1$. For $x > x_1$ we have, for all x_2,

$$\left.\begin{aligned} \tilde{R}_p(E_1, x_2) &= R_p(E_1), \\ & \quad x > x_1. \end{aligned}\right\} \tag{15}$$

Equation (8) becomes

$$x_2 = x_1 + R_p(E_1) \tag{16}$$

As will be discussed in Section VI, this expression is equivalent to what was used in references 6 and 4.

Case B: Uniform Stretching

Here we choose

$$\widetilde{R}_p(E, x_2) = C(x_2)R_p(E) \tag{17}$$

with the constant C chosen such that

$$x_2 = C\,R_p(E_B) \tag{18}$$

Equation (8) than gives

$$R_p(E_1) = 1 - \left(x_1/x_2\right)R_p(E_B) \tag{19}$$

as will be discussed in Section VI, this expression is equivalent to what was used in references 7, 8, and 9. The corresponding energy distribution was used by Marwick (8) to calculate PKA recoil spectrum.

Case C: Fluctuations Proportional to Range Straggling

Here we choose

$$\widetilde{R}_p(E, x_2) = R_p(E) + C(x_2)\alpha(E), \tag{20}$$

with the constant C chosen such that

$$x_2 = R_p(E_B) + C\alpha(E_B). \tag{21}$$

In this case the model fluctuations are proportional to range straggling

$$\widetilde{R}_p(E, x_2) - R_p(E) = C\alpha(E) \tag{22}$$

Equation (8) becomes

$$x_2 = x_1 + R_p(E_1) + \left(\alpha(E_1)/\alpha(E_B)\right)\left((x_2 - R_p(E_B)\right). \tag{23}$$

Energy Deposition Profiles

As a beam particle traverses the target, it deposits energy into elastic collisions given by (2).

$$S_n(E) = (dE/dR)_{\text{elastic}} = \int_0^\infty T\,d\sigma_n, \tag{24}$$

where T is the target atom recoil energy, and $d\sigma_n$ is the atomic section for elastic collisions. The corresponding quantity for (dE/dx) can be approximated as

$$(dE/dx_{elastic}) \quad S_m(E)\,(dR(E)/dR_p). \tag{25}$$

The profile $S_p(x)$ for energy deposited into elastic collisions by the entire ion beam as it traverses the depth x can be written

$$S_{B1}(x) = \int_0^\infty dE\; g(E,x)\; S_n(E). \tag{26}$$

A more refined approximation can be obtained by employing the expression (25) (Reference 3):

$$S_{B2}(x) = \int_0^\infty g(E,x)\; S_m(E) \left(dR(E)/dR_p\right). \tag{27}$$

A still more refined approximation can be obtained by including the LNST theory for energy partition (5) to obtain (3)

$$S_D(x) = \int_0^{E_B} dE_g(E,x)\; S_L(E) \left(dR(E)/dR_p\right), \tag{28}$$

where

$$S_L(x) = N \int T\,\eta(t)\; d\sigma \tag{29}$$

and η (T) is the LNST partition function.

On using the relation (7), the above energy dispostion profile becomes:

$$S_B(x_1) = \int_{X_1}^\infty dx_2\; f(x_2)\; S_m(E_1), \tag{30}$$

$$S_{B2}(x_1) = \int_{X_1}^\infty dx_2\; f(x_2)\; S_m(E_1) \left(dR(E)/dR_p\right), \tag{31}$$

and

$$S_D(x_1) = \int_{X_1}^\infty dx_2\; f(x_2)\; S_L(E_1) \left(dR(E_1)/dR_p\right). \tag{32}$$

For case A, S_B of equation (29) becomes the energy deposition profile calculated by Kulcinski, Laidler, and Doran (6), while S_{B2} and S_D of equations (31) and (32) become the quantities calculated by Manning and Mueller with the computer code E-DEP-1 (4). For case B, S_D of equation (32) becomes the energy deposition profile calculated by Johnston, Rosalowski, Turkalo and Lauritzen (7), as described by Marwick (8) and further disucssed by Matthews (9).

Marwick (8) and Matthews (9) point out that for case A one obtains a non-physical energy distribution at the target surface whereas for case B, one correctly obtains $E = E_B$ as the only allowable energy. These results are readily confirmed by examination of equations (16) and (19) at the point $x = 0$. We see from equation (23) that case C also has the correct energy distribution at the surface.

Acknowledgement

The author has profited from conversations with W. A. Fraser, G. P. Mueller, and M. Rosen.

B. Approximation for Energy Deposition in Ion Beam Bombardment

(Irwin Manning, Radiation-Matter Interaction Branch,
Radiation Technology Division)

Introduction

As do some other energy deposition calculations for ion beam bombardment, the NRL Code E-DEP-1 makes the approximation that a primary knockon atom (PKA) deposits its energy close to the site of creation (4). For low bombarding energies this approximation can lead to large errors, since the PKA in actuality deposits energy downstream from its creation site. Brice has formulated a method for taking those recoil effects into account (10). The present work formulates a different approach for calculating these effects by making extensive use, in the spirit of Reference (11), of a table of range distributions, the present work makes different (and probably milder) approximations than does Brice.

Notation for Elastic Collisions

As in Reference (11), we consider a beam of ions with atomic number Z, and energy E_B bombarding, in slab geometry, an amorphous target of atoms with atomic number Z_2. To distinguish binary collisions between beam-target atoms from binary collisions between target-target atoms, we shall denote the former by subscript 12 and the latter by 22.

We shall write the elastic cross section as $K_{12}(E,T)$, where E is the energy of the (Z_1) beam atom, and T is the recoil energy of the (Z_2) target atom. We have, for the penetrating beam

$K_{12}(E,T)\, dT\, dR$ = number of Z_2 recoils of energy dT about T produced per unit time as an ion beam of unit fluence and energy E traverses a path length dR through a unit perpendicular area. (1)

For an ensemble of penetrating ions Z_1, we also have

$K_{12}(E,T)\, dT dR$ = ensemble average of the number of recoils of energy dT about T produced as a penetrating ion Z_1 of energy E-traverses a path length dR (2)

For the elastic energy loss we have

$$Sn_{12}(E) = (dE/dR)_{elastic} = N \int dT\, T\, K_{12}(E,T) \qquad (3)$$

where N is the density of target atoms.

Let $\phi(E,x)$ be the energy distribution of the penetrating (Z_1) beam defined in Reference 11 and let $\psi(T,x)$ be the distribution function for PKA's (that is, recoils produced in 12 collisions) produced by this beam:

$\psi(T,x)\,dT$ = number of PKA's of energy dT about T produced per unit time per unit bombarding beam flux as an ion beam with distribution $\phi(E,X)$ traverses a perpendicular unit area located at depth x. (4)

We have

$$\psi(T,x) = \int dE\ \phi(E,x)\ K_{12}(E,T)\ \ dR_{12}(E)/dR_p. \tag{5}$$

Energy Deposition by a PKA

Consider a PKA created at the point A at depth x_1 with energy T_1 and velocity direction $\hat{v}_1$. We will assume no range straggling for Z_2 atoms. Our model has range and energy straggling only for the beam (Z_1) atoms. We also assume that the PKA travels in a straight line, coming to rest at a point C. Let B be an intermediate point at depth x_2, where the PKA has energy T_2. Let μ be the cosine of the angle between $\hat{v}_1$ and the x-axis:

$$\mu(E_1,T_1) = \hat{v}_1 \cdot \hat{x}\ ; \tag{6}$$

the kinematics of elastic collision determines μ as a function of E_1 and T_1, where E_1 is the energy of the Z_1 beam ion creating the PKA. We have

$$x_2 - x_1 + \mu(E_1,T_1)\,R_{P22}(T_2) = R_{P22}(T_1) \tag{7}$$

This equation determines T_2 as a function of T_1 and E_1:

$$T_2 = T_2(E_1, T_1) \tag{8}$$

Now let $S_P(x_2, x_1, T_1)\,dx_2$ be the damage energy deposited by this PKA as it traverses a depth dx_2 around the point B. We have

$$S_P(x_2,x_1, T_1) = S_P(x_2 - x_1, T_1)$$

$$= \left(1/\mu(E_1, T_1)\right) \eta_{22}(T_2)\, S_{m22}(T_2) \left(dR_{22}(T_2)/dR_P\right), \tag{9}$$

where $\eta_{22}(T)$ is the energy partition factor of Lindhard, Nielsen, Scharff, and Thompson (1).

Energy Deposition by the Bombarding Beam

For a bombarding beam, the damage energy deposited at the point x_2 is obtained by multiplying the expression (9) by the number of PKA's of energy T_1 produced at x_1 and summing over T_1 and x_1. We will denote by $S_{DR}(x_2)$ the damage energy including recoil effects:

$$S_{DR}(x_2) = \int_0^{X_2} dx_1 \int_{E_d}^{T_m} dT_1 \quad S_P(x_2, x_1, T_1)\psi(T_1, x_1). \tag{10}$$

Equation (5) gives

$$S_{DR} = \int_0^{X_2} dx_1 \int_E^{T_m} dT_1 \int dE_1 \, S_P(x_2, x_1, T_1)\phi(E_1, x_1)$$

$$K_{12}(E_1, T_1) \left(dR_{12}(E_1)/dR_P \right) \tag{11}$$

Let x_3 be the stopping depth of the Z_1 beam ion which creates the PKA of energy T_1 at depth x_1; this Z_1 ion has energy E_1 at the depth x_1. Using the methods of Reference (11), we can employ the range distribution $f(x_3)$ of Z_1 ions to estimate the flux $\phi(E_1, x_1)$ of equation (11), obtaining

$$S_{DR}(x_2) = \int_0^{X_2} dx_1 \int_{E_d}^{T_m} dT_1 \int_{X_1}^{\infty} dx_3 \, S_P(x_2 - x_1, T_1)$$

$$K_{12}(E_1, T_1) \; (dR_{12}/dR_P) \, f(x_3) \tag{12}$$

Now, interchange the order of integration of x_3 and T_1, and define

$$S_M(x_2 - x_1, E_1) = \int_{E_d}^{T_m} dT_1 \; K_{12}(E_1, T_1) \, S_P(x_2 - x_1, T_1) \tag{13}$$

with S_P given by equation (9).

$S_M dx_2$ is the damage energy dE_M deposited at dx_2 around x_2 by all the PKA's created at depth x_1 by a single beam ion Z_1 with energy E_1.

Define $S_{M2}(x_2 - x_1)$ as

$$S_{MS}(x_2 - x_1) = \int_{X_1}^{\infty} dx_3 \, S_M(x_2 - x_1, E_1) \left(dR_{12}(E_1)/dR_P \right) f(x_3) \tag{14}.$$

S_{MS} is the damage energy function S_M for a penetrating beam with the energy straggling given by the distribution function $\phi(E_1,x_1)$. We now get the desired energy profile S_{DR} of equation (12) as

$$S_{DR}(x_2) = \int_0^{x_2} dx_1 \; S_{MS}(x_2-x_1). \tag{15}$$

Acknowledgment

The author has profited from conversations with W. A. Fraser, M. Rosen and G. P. Mueller.

II. HEAVY ION AND NEUTRON DAMAGE STUDIES

A. The Effect of Alloy Additions on the Swelling of Neutron-Irradiated Nickel

(J. A. Sprague, K. B. Roarty, and F. A. Smidt, Jr.
Thermostructural Materials Branch,
Material Science & Technology Division)

Background

Swelling (or volume change) of materials caused by high-fluence neutron irradiation at elevated temperatures is a major engineering design problem that limits the performance of advanced nuclear reactors. This swelling is caused by the agglomeration of radiation-produced vacancies into microscopic cavities or voids. The design of new low-swelling alloys for nuclear applications requires fundamental knowledge of the effect of individual alloying elements in simple binary alloy systems, since individual effects cannot be readily studied in the more complex commercial alloys. The present study was undertaken to examine the effects of small additions of aluminum, molybdenum, silicon, and titanium on void formation in neutron-irradiated nickel. These data were then compared with the results of previous work (12) that involved nickel-ion irradiation of the same set of alloys. This comparison provides insight into the effects of alloying on both the swelling of nickel and the correlation between neutron and heavy-ion damage.

Progress

The pure nickel control material and the nickel alloys used in the present study were taken from the alloy series previously examined following nickel-ion irradiation (12). The alloys Ni-1 at.%Al, Ni-1 at.%Mo, Ni-1 at.%Si, and Ni-1 at.%Ti were selected for the first examinations following neutron irradiation. The ion irradiation experiments had shown that the swelling in Ni (at 8.1 dpa* 625°C) was reduced by a factor of 40 by the Al addition, and that significant void formation was completely suppressed by the Mo, Si, and Ti additions.

The alloys and the control material were all prepared by arc-melting ∿65-gram buttons in an argon atmosphere, which had been purified by titanium gettering. After several remelts, a 3-mm thick slice was sectioned from the center of each button. The slices were cold-rolled to 0.1-mm thick foil, from which 3-mm diameter disks were punched. With the exception of the Al alloy, these specimens were annealed for one hour at 990°C in a 1×10^{-6} torr vacuum. The Ni-1%Al specimens were similarly annealed, but the temperature was reduced to 800°C to reduce the loss of Al from the foils.

*The original reference calculated dpa values using a displacement energy of 25 eV for nickel, while the present report uses 40 eV to conform with current convention.

The disks were irradiated in the Experimental Breeder Reactor No. II (EBR-II) fast reactor in Idaho Falls, Idaho, to a neutron fluence of 2.2×10^{22} neutrons/cm^2, E> 0.1 MeV, at a temperature of 455°C. Following irradiation, disks were thinned by dual-jet electropolishing in a solution of 250 ml methyl alcohol, 150 ml n-butyl alcohol, and 10 ml perchloric acid at a temperature of -60°C and a voltage of 35 V. Void and dislocation structures were studied by transmission electron microscopy.

The dislocation structures in all of the materials consisted primarily of tangles of line dislocations. This is illustrated in Fig. 1, which shows the structure observed in the pure Ni. As is normally observed in specimens containing voids, the dislocation lines tended to interconnect the voids.

The qualitative features of the void distributions observed in Ni, Ni-1%Al, Ni-1%Mo, Ni-1%Si, and Ni-1%Ti are shown in Figs. 2 - 6, respectively. Quantitative parameters measured from these void structures are given in Table 1. The following features of void formation in these materials can be seen:

1. The void size distribution in the pure Ni was very broad, and the voids were formed heterogeneously, with clusters of small voids dispersed among larger ones.

2. In the Ni-Al alloy, the void size distribution was narrower, and the spatial distribution of the voids was more homogeneous, but the average size, number density, and swelling were similar to the pure Ni.

3. The Mo and Ti additions both increased the swelling by approximately a factor of two, but by different mechanisms. The Mo increased the void nucleation but did not affect the void growth, leading to a higher density of similarly-sized voids. The Ti, on the other hand, did not appear to alter the void nucleation, but increased void growth, leading to a similar density of larger voids.

4. The Si addition produced the only reduction in swelling of the four alloying elements, decreasing it by approximately a factor of ten. The Si did not significantly change the void number density, but considerably reduced the mean void size.

These observed alloying effects on void formation differ significantly from the previously reported nickel-ion experiments on the same alloys (12). As noted above, all four of the alloying elements reduced or completely suppressed the swelling in the Ni-ion-irradiated Ni, by reducing the void nucleation (assuming that the ion-irradiated specimens did not contain a high density of voids smaller than the $\sim$1.5 nm resolution limit of the microscope). A thorough understanding of the differences between neutron and nickel-ion irradiations of these alloys would require a much more extensive investigation of irradiation temperatures and damage levels for both irradiating particles. Experimental and theoretical models which are currently available, however, offer some potential explanations. A study of the swelling produced in pure Ni

Fig. 1

The dislocation structure observed in pure nickel following irradiation with 2.2×10^{22} neutrons/cm^2, $E > 0.1$ MeV, at 455°C. The dislocation structures observed in Ni-1 at.%Al, Ni-1 at.%Mo, Ni- 1 at.%Si, and Ni-1 at.%Ti were qualitatively similar.

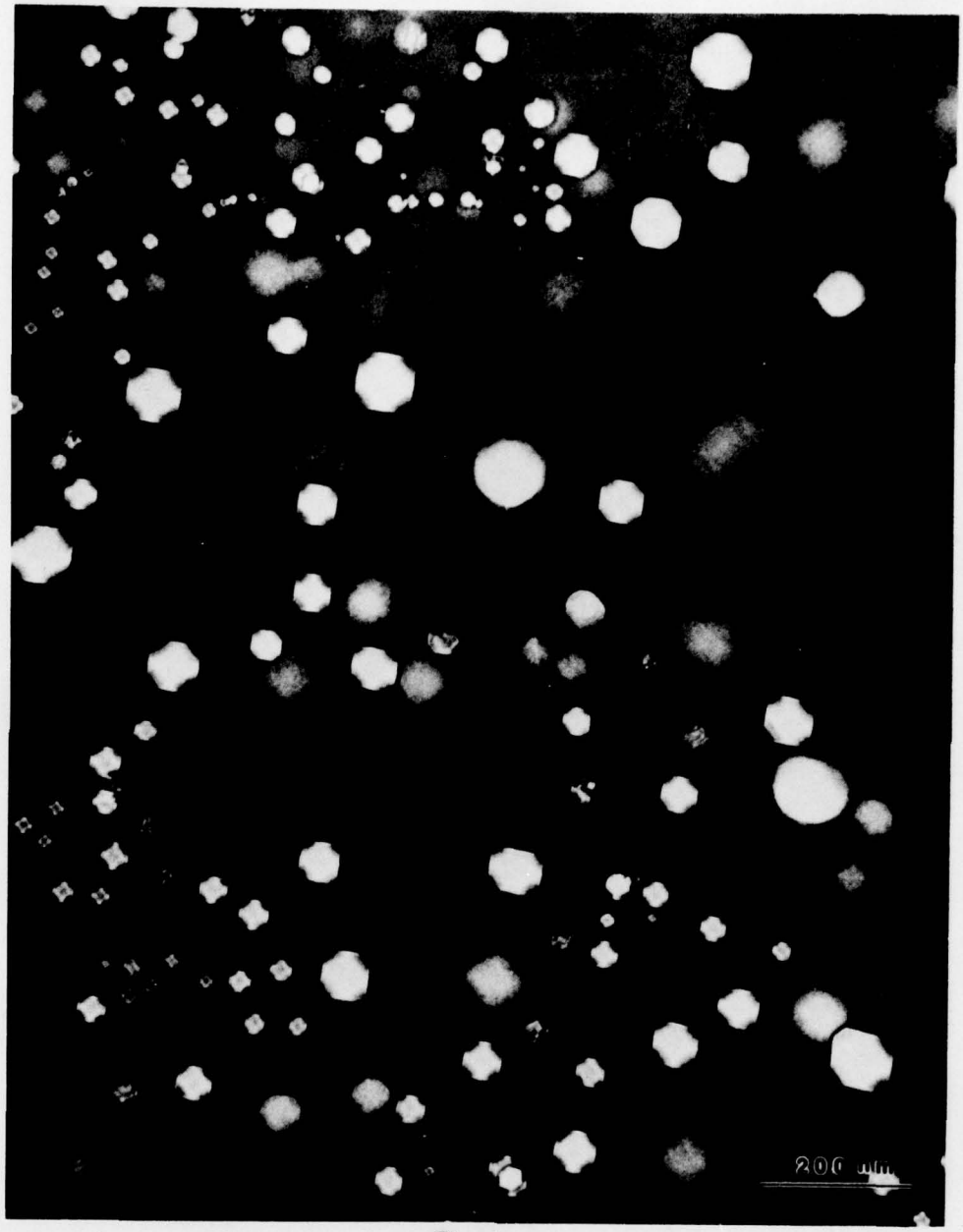


Fig. 2

Void distribution observed in pure Ni following irradiation with 2.2 x 10^{22} neutrons/cm^2, E >0.1 MeV, at 455°C.

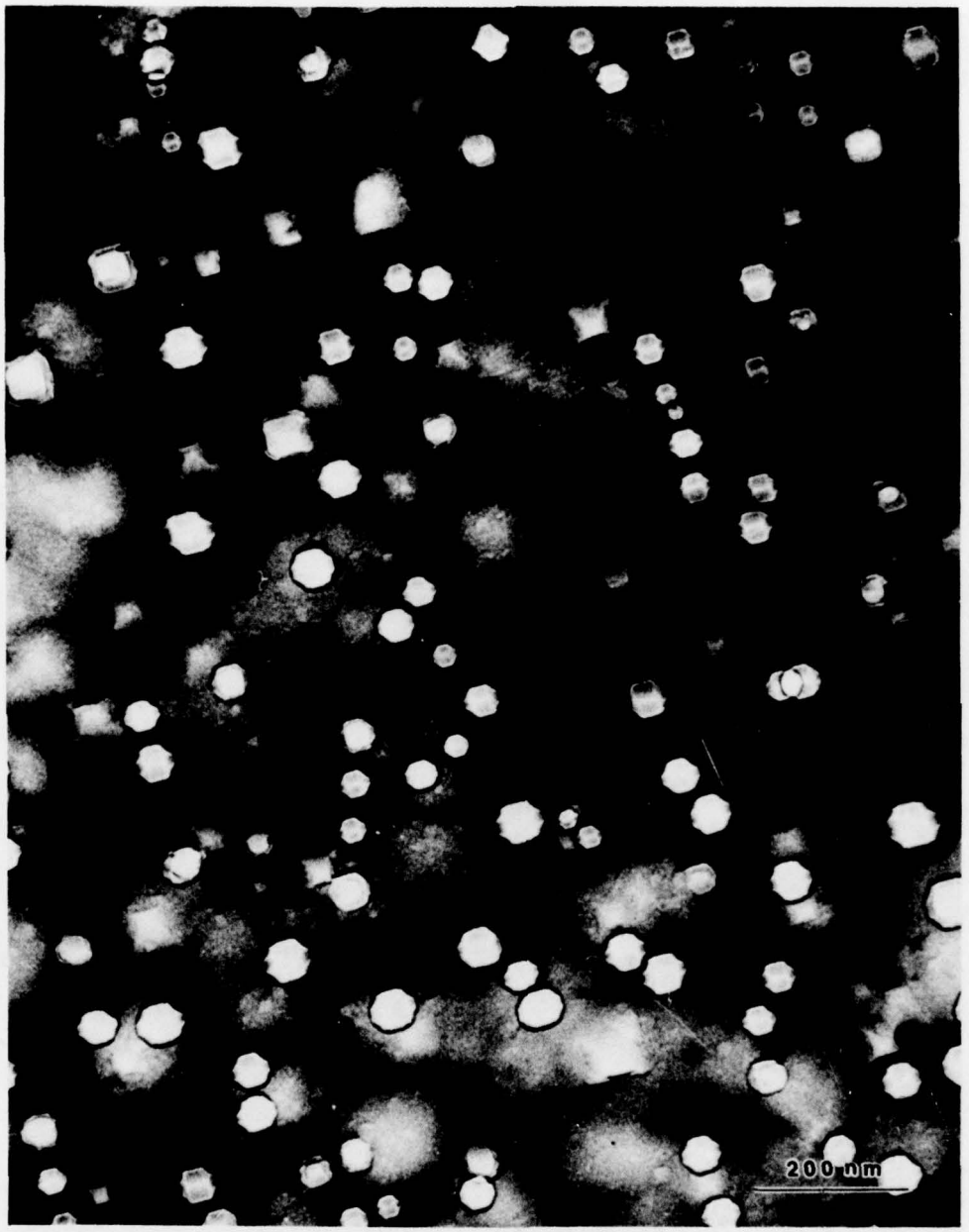


Fig. 3

Void distribution observed in Ni-1 at.%Al following iradiation with 2.2×10^{22} neutrons/cm^2, E >0.1 MeV, at 455°C.

Fig. 4

Void distribution observed in Ni-1 at.%Mo following irradiation with 2.2×10^{22} neutrons/cm^2, E >0.1 MeV, at 455°C.

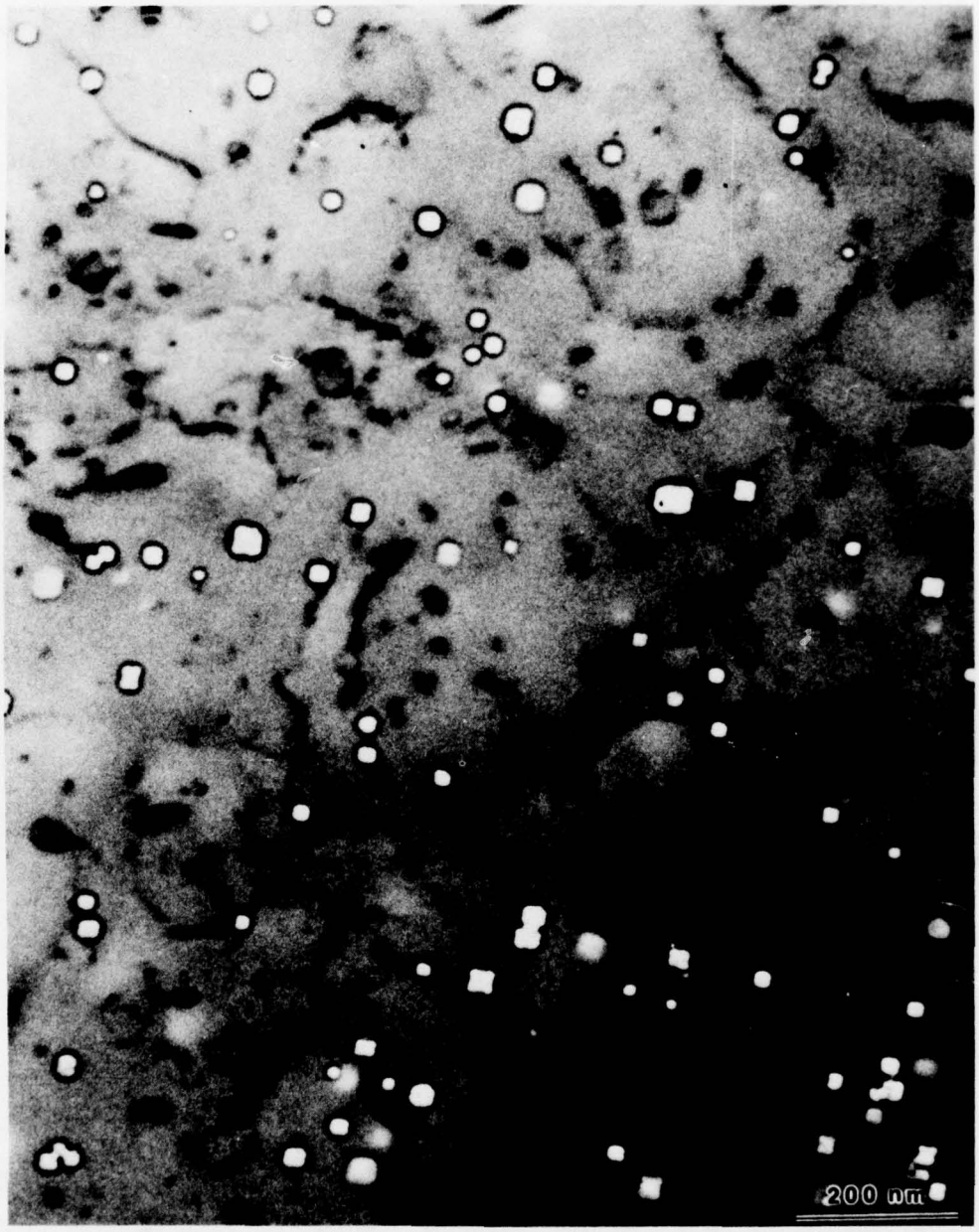


Fig. 5

Void distribution observed in Ni-1 at.%Si following irradiation with 2.2×10^{22} neutrons/cm^2, E >0.1 MeV, at 455°C.

Fig. 6

Void distribution observed in Ni-1 at.%Ti following irradiation with 2.2×10^{22} neutrons/cm^2, E >0.1 MeV, at 455°C.

TABLE 1

VOID FORMATION IN NICKEL ALLOYS

(2.2×10^{22} n/cm^2, 455°C)

Material	Void Density (cm^{-3})	Mean Void Dia (nm)	Swelling (%)
Ni Control	3.5×10^{14}	43.5	2.56
Ni-1% Al	4.2×10^{14}	48.8	3.04
Ni-1% Mo	1.33×10^{15}	41.0	5.64
Ni-1% Si	3.8×10^{14}	21.0	0.27
Ni-1% Ti	2.8×10^{14}	62.1	4.91

by neutron and Ni-ion irradiations (13) concluded that different void nucleation mechanisms were controlling void formation in the two cases. In the ion irradiation experiments, the displacement rate was 4.4×10^{-2} dpa/sec,* which produces large supersaturations of vacancies and interstitials, which can lead to significant void nucleation in the absence of insoluble gasses (14). In a fast reactor irradiation, however, displacement rate is $\sim 1 \times 10^{-6}$ dpa/sec, and the helium produced by transmutation reactions is probably responsible for driving the void nucleation. It is therefore possible that all four alloying elements in this study could greatly reduce the homogeneous nucleation rate in a Ni-ion irradiation while either having no effect on the helium-assisted nucleation mechanism that is dominant in a neutron irradiation, or even enhancing this mechanism. A second factor which could have influenced these experiments is radiation-induced segregation of the alloying elements. In other studies (15), it has been found that alloying elements which trap vacancies or interstitials will not only affect the void nucleation and growth, but will also segregate with respect to internal point defect sinks, such as voids and dislocations. This segregation can change the rates at which these sinks absorb vacancies and interstitials, as well as reduce the amount of a solute element in solution in an alloy matrix. Both of these effects can alter the void formation in an alloy. The extent of radiation-induced solute segegation is a strong function of the damage rate, so that it will be very different in neutron and nickel-ion irradiations.

The present neutron-irradiation experiments, together with the previous ion-irradiation work on the same alloys, have demonstrated that low concentrations of solid-solution alloying elements can significantly change the void formation behavior of nickel. More importantly, these studies indicate that caution should be exercised in evaluating high-dose-rate ion irradiations of complex alloys. The effects of damage rate on all important processes, including nucleation mechanisms and solute segregation, must be considered if such ion irradiation experiments are to accurately reflect the relative swelling behavior of the alloys during reactor irradiations.

B. The Microstructure of Neutron Irradiated Refractory Metals and Alloys

(J. A. Sprague, F. A. Smidt, Jr., and J. R. Reed,
Thermostructural Materials Branch,
Material Science & Technology Division)

Background

Alloys based on the bcc refractory metals are of interest for high temperature nuclear systems, such as fusion power reactors, because of the high operating temperatures, and thus high power densities, possible with this class of materials. The engineering application of refractory alloys will require the expansion of our current data base on these materials and their behavior during high-fluence irradiation at elevated temperature. The present experiments, which are closely related to the work of the CORES program, were performed as part of the Fusion Materials Program of the Office of Fusion Energy, U. S. Department of Energy. The objective was to study the microstructural response of molybdenum, TZM, niobium, niobium-1% zirconium, vanadium, and vanadium-20% titanium to high fluence neutron-irradiation at 650°C. These results supplement previous work by a number of investigators to provide a basis for the more systematic and comprehensive experiments that will be required to adequately define the irradiation response of refractory metals and alloys.

Progress

Experimental Procedures. The pure Mo (>99.95%), Nb (>99.99%), and V (>99.95%) were obtained from Materials Research Corporation in the form of 50-μm thick foil. (Note that the above nominal purities are for substitutional solutes only.) The TZM (Mo-0.5 wt.% Ti-0.1 wt.% Zr), Nb-1 wt.% Zr, and V-20 wt.% Ti materials were rolled to 50-μm thick foil from commercial-grade stock. Following the punching of 3-mm dia. disks, the metals and alloys were all annealed in a vacuum of 1.3×10^{-4} Pa for 1 hour at 1430°C, except for the V and V-20 Ti, which were annealed at 885°C. The foils were packed into close-fitting stainless steel tubes which were evacuated, back-filled with helium, and welded shut. The foil tubes were loaded into sodium-filled heat pipe-controlled irradiation capsules (16) for irradiation in the EBR-II reactor. Two capsules were used in the present experiments, both designed to operate at 650 ±10°C. The first (EBR-II subassembly X-200), which contained all materials except the V-20 Ti, was irradiated in Row 7 to a fluence of 5.4×10^{22} neutrons/cm^2, E >0.1 MeV. The second capsule (EBR-II subassembly X-255) containing the Mo and V-20 Ti was irradiated in several positions, mostly in Row 2, to a fluence of 8.4×10^{22} neutrons/cm^2, E >0.1 MeV. Assuming a 40 eV displacement energy for all the materials, the lower neutron fluence corresponds to 22 dpa for Mo and TZM, 21 dpa for Nb and Nb-1 Zr, and 24 dpa for V. The higher neutron fluence corresponds to 35 dpa for Mo and 38 dpa for V-20Ti. Following irradiation, the foils were electrochemically thinned and examined by transmission electron microscopy.

Results and Discussion

The experimental results will be discussed in each of the following subsections by comparing each pair of pure metal and alloy, in turn. The quantitative void distribution data for those materials that exhibited significant void formation are all collected in Table 2, and will be referenced in each subsection, as needed.

Mo and TZM. The microstructures of the Mo at both fluences and the TZM at the lower fluence were similar, consisting of imperfectly ordered void lattices and moderate densities of dislocation loops and line segments. Examples of these microstructures are shown in Fig. 7. The total dislocation density in each of the specimens examined was in the range 5 - 7 x 10^{9} cm^{-2}. A low density of globular precipitates was observed in the TZM. In the pure Mo, a void lattice parameter of 30 nm was measured for both fluences, which is in good agreement with previous lower-fluence measurements of void lattice parameter as a function of irradiation temperature (17,18). Some ordering, on approximately the same scale as in the Mo, could be detected in the TZM, but a good void lattice parameter determination could not be made, due to the relatively large size of the voids and the imperfections in the ordering. Referring to the void distribution data in Table 2, it can be seen that the swelling measured in TZM at the lower fluence was slightly greater than that in the pure Mo, although the difference was within the error limits for these determinations. At the higher fluence, where the only data were for the pure Mo, the swelling was actually smaller than at the lower fluence, although the difference was again within error limits. Both void densities and mean diameters in the Mo were similar at both fluences. The TZM contained a lower density of significantly larger voids, a number of which appeared to have coalesced from multiple smaller voids formed earlier in the irradiation. A final observation was that the voids in the pure Mo were surrounded by the strong strain fields, which were easily visible in dark field, using a $<110>$g-vector. No strain fields of similar magnitude were observed surrounding the voids in TZM.

The present observation of the relative swelling in Mo and TZM agrees fairly well with previously reported results of other investigators, although there are significant differences in relative void sizes and number densities. At low neutron fluences ($\sim 10^{20}$ n/cm^2), Bentley, et. al (19) reported significant void formation in Mo over the entire temperature range 330 - 850°C, while they observed significant void formation in TZM only for "intermediate" temperatures in this range. At higher fluences of 2.5 - 4.4 x 10^{22} n/cm^2, E > 0.1 MeV, Bentley and Wiffen (17) observed comparable swelling in Mo and TZM at 425 and 585°C, and slightly greater swelling in TZM at 790 and 1000°C. The void number densities observed in pure Mo in the present study are consistent with the temperature dependence of void number density reported by Bentley and Wiffen. There is a significant difference, however, between the void population reported by Bentley and Wiffen in TZM and those observed in the present study. Compared with pure Mo, they observed a higher density of smaller or equal size voids in TZM at all temperatures between 425 and 1000°C, while the present study found a lower density of larger voids in TZM. Another difference between the present results and those in the literature is with those reported by Sikka and Moteff (18) for irradiation to a fluence of 1 x 10^{22} n/cm^2 E > 1 MeV, at temperatures between 430 and 1000°C. Although this fluence corresponds to 21 dpa, the same as the present

TABLE 2

VOID DISTRIBUTIONS OBSERVED AFTER NEUTRON IRRADIATION AT 650°C

Material	Fluence (n/cm^2, E > 0.1 MeV)	Void Density (cm^{-3})	Mean Diam. (nm)	Swelling (%)
Mo	5.4×10^{22}	1.0×10^{17}	7.8	3.0
Mo	8.4×10^{22}	9.8×10^{16}	7.2	2.3
TZM	5.4×10^{22}	5.2×10^{16}	10.5	4.0
Nb	5.4×10^{22}	2.1×10^{17}	4.6	1.5
V	5.4×10^{22}	5.5×10^{14}	42.1	3.6

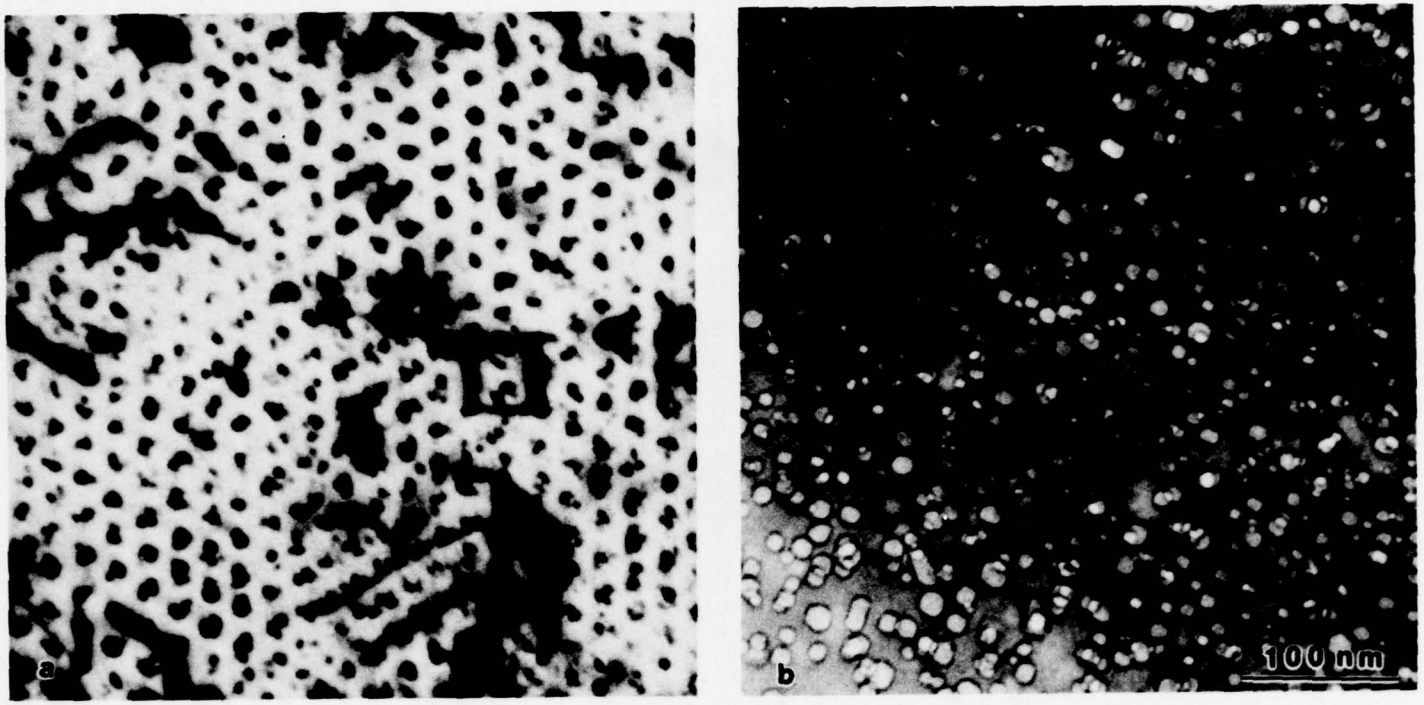


Fig. 7

Representative void structures in irradiated Mo and TZM: (a) Mo, imaged with a [111] beam direction showing void ordering; the voids appear dark due to a combination of overfocus and strain contrasts; (b) TZM, in which several coalesced voids can be seen.

study, their reported temperature dependence implies only approximately 10 percent of the presently observed swelling. The reasons for the above discrepancies are not known at this time.

Nb and Nb - 1% Zr. The Nb contained a very high density of small voids, as illustrated in Fig. 8a, as well as a much lower density of small ($\sim$10 nm) precipitates in the matrix. The void lattice parameter, assuming a bcc structure, was 24 nm. The swelling, as seen from the data in Table 2, was considerably less than that in the other pure metals or the TZM. Prior to irradiation, the Nb-1 Zr contained a few precipitates at the grain boundaries. After irradiation, the alloy contained additional precipitates, both at the grain boundaries and in the matrix, as seen in Fig. 8b. A few voids, $\sim$5 nm in diameter, were observed in isolated areas of the foil, but these did not represent any significant swelling. This observation of suppression of swelling in Nb-1Zr agrees with the results of Michel and Moteff (20) and Jang and Moteff (21), who both reported significant swelling in Nb-1Zr only over the temperature range 700 - 900°C at a neutron fluences of 2.5×10^{22} n/cm^2 (20) and 5×10^{22} n/cm^2 (21), E > 0.1 MeV. The void distribution observed in Nb in the present study, however, was quite different from that reported by Michel and Moteff in that the voids observed here were smaller, and the number density was approximately an order of magnitude larger. The reasons for this difference cannot be determined unambiguously, but they are probably related to the impurity contents of the materials in the two studies. First, the material used in Michel and Moteff's work was commercial-grade Nb, as opposed to the high-purity stock used in the present experiment. Second, the specimens in the present study were annealed as 50-μm thick foil in a 1.3×10^{-4} Pa vacuum at 1430°C. Although the specimen holder in the furnace was made of tantalum, considerable contamination (on the order of a few thousand parts per million) by interstitial impurities probably occurred (22). This conclusion is reinforced by the observed precipitation. The preirradiation annealing conditions for the material used in Michel and Moteff's work were not specified. It seems reasonable, therefore, that differences in substitutional and interstitial impurity contents were responsible for the different void distributions.

V and V-20% Ti. The microstructure of the irradiated pure V was quite different from those of the Mo and Nb, as shown in Fig. 9a. The preirradiation annealing treatment had produced a fine grain size (5 - 10 μm), and after irradiation, each grain contained a moderate density of fairly large voids. The voids were denuded near each grain boundary. The dislocation density in the grain interiors was low, $\sim 1 \times 10^9$ cm^{-2}, although many dislocations were observed in subgrain boundaries. No precipitates were observed. The preirradiation microstructure of the V-20Ti contained a heterogeneous distribution of precipitates, the diffraction patterns of which were consistent with hexagonal TiO_2 (rutile). The maximum observed local number density of these precipitates was 2×10^{13} cm^{-3}, while the average density over a larger specimen volume was $\sim 4 \times 10^{12}$ cm^{-3}. A detailed characterization of the precipitate size distributions was not made, but two morphologies were observed: blocky precipitates with a 150 nm mean diameter, and rod-shaped, $\sim$100 nm in cross section and 200 - 400 nm long. Irradiation of this material at 650°C to 8.4×10^{22} neutrons/cm^2, E >0.1 MeV, produced no observable voids, but did result in significant growth of the precipitates. The mean diameter of the blocky particles increased to 500 nm; the mean cross section of the rod-shaped precipitates was 150 nm, while the maximum length of the rods increased to 1500 nm. A

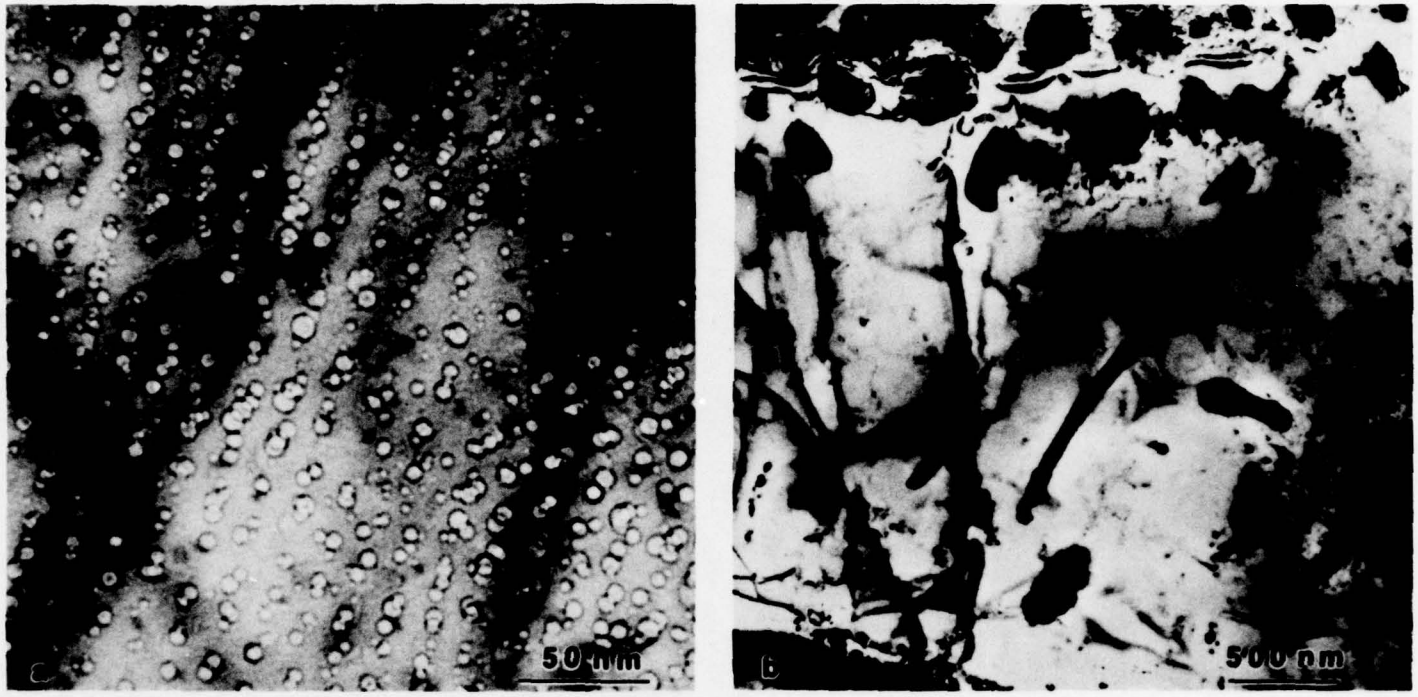


Fig. 8

Representative microstructures in irradiated Nb and Nb-1%Zr: (a) Nb, containing a high density of small voids; (b) Nb-1% Zr, with no void formation, but extensive matrix and grain boundary precipitation. Note the different magnifications in the two micrographs.

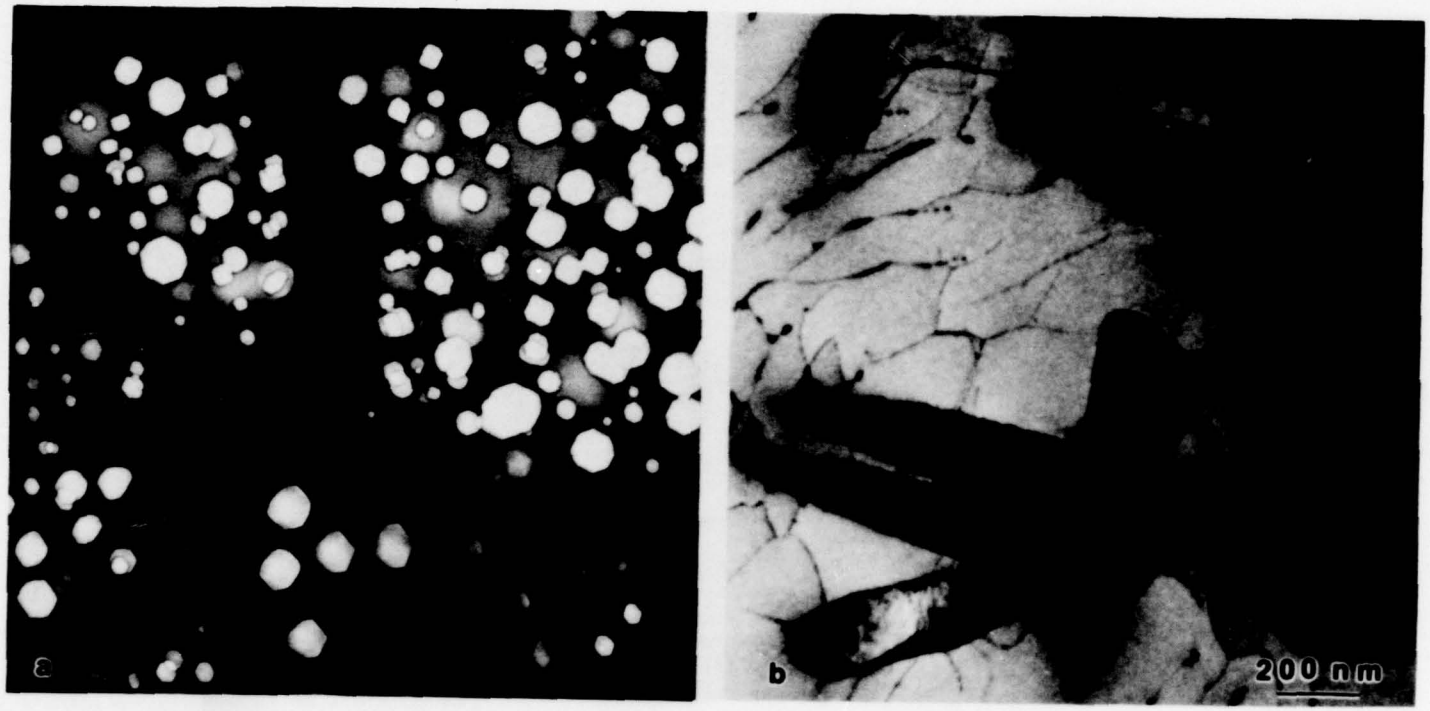


Fig. 9

Representative microstructures in irradiated V and V-20% Ti: (a) V, showing the denuding of voids at boundaries of the small grains; (b) V - 20% Ti, containing elongated TiO_2 precipitates which increased in maximum length from 400 to 1400 nm during irradiation.

cluster of the elongated precipitates in the V-20Ti is shown in Fig. 9b.

The complete suppression of void formation by the addition of 20% Ti to V agrees with the results of Bentley and Wiffen (23), who examined V-20Ti irradiated to fluences of 1.3 - 6.1 x 10^{22} n/cm^2, E > 0.1 MeV, at temperatures between 470 and 780°C. Before irradiation, their specimens contained precipitates similar in size, shape, and maximum number density to those observed prior to irradiation in the present study, although they reported that the specimen regions containing this maximum number density represented only ∿ 1% of the specimen volume. They observed no change in this preirradiation precipitate structure after irradiation. Carlander (24) reported a few voids in V-20Ti after irradiation to 6 x 10^{22} n/cm^2, E > 0.1 MeV, at 600°C, although these voids did not represent any significant swelling. He did not report on the precipitation behavior of this alloy, but a number of apparent rod-shaped precipitates can be seen in his published micrograph (Fig. 3 of Carlander, Reference 24).

The void microstructures in the pure V are difficult to correlate with those reported previously for lower fluence irradiations (24,25), due to differences in starting materials and irradiation temperatures, but the observation of 3.6% swelling at 5.4 x 10^{22} n/cm^2 is consistent with approximately linear swelling with fluence, when compared with the 1.54% swelling reported by Carlander (24) for irradiation to 2.5 x 10^{22} n/cm^2 at 625°C and the 1.47% swelling reported by Stiegler (25) for irradiation to 1.4 x 10^{22} n/cm^2 at 600°C (all fluences for E >0.1 MeV).

Conclusion

The present microstructural observations of refractory metals and alloys after high-fluence neutron irradiation at 650°C indicate that, at least at this temperature, void swelling will probably not be the most serious obstacle to the application of this class of alloy. The swelling of even the pure metals is only moderate, and with the possible exception of Mo alloys, it appears possible to control void formation further by alloying. Changes in mechanical properties due to precipitation of interstitial impurities and the formation of high densities of small voids may be far more serious problems. Theoretically, the precipitation could be controlled by reducing the concentration of interstitial contaminants, but more comprehensive studies on thoroughly characterized materials will be required to examine this possibility. If detrimental changes in microstructure can be avoided by careful control of impurities, fabrication technologies and reactor operating conditions will still have to be developed to maintain this impurity control in large structures. If these developments can be made, however, refractory metal alloys appear to be potentially valuable for high temperature nuclear applications.

III. LIGHT ION BEAM STUDIES

A. Deuterium Retention in Aluminum and Stainless Steel With and Without Helium Loading

(L. A. Beach, Cyclotron Applications Branch,
Radiation Technology Division)

Fast neutrons in high flux reactors generate hydrogen and helium in reactor structural materials by (n,p) and (n, α) reactions. Helium is known to accumulate in metals and alloys under reactor operating conditions and its accumulation is intimately related to swelling and other changes in mechanical properties. It has generally been assumed that hydrogen, although generated in larger amounts than helium, diffuses or permeates through the material and consequently not causing any mechanical property changes. However, retention of appreciable amounts of hydrogen could lead to deleterious effects.

Lanford (26) reported that hydrogen implanted into single crystal silicon wafers was retained indefinitely but that hydrogen retention in tungsten was enhanced with helium predamage with little retention in samples of tungsten without predamage. Nowicki (27), based upon hydrogen profile measurements by Pieper at NRL, showed that large amounts of hydrogen were present in rf-spattered Al_2O_3 films deposited by planer magnetron, it remained stable and affects mechanical properties. Picraux (28) has shown enhanced hydrogen and deuterium retention in molybdenum with helium predamage, both for single crystal samples and rolled foil. Since helium is known to become substitutional by falling into vacancies created by atomic displacements and positrons have been observed to attach to these helium filled vacancies, the possibility exists that hydrogen, which would normally remain interstitial and diffuse through the metal, may attach itself to these filled vacancies.

In controlled thermonuclear systems high fluxes of 14-MeV neutrons will bombard structural materials including first walls, blankets and cyrogenic cooling systems. The generation of hydrogen and helium will be enhanced by the higher cross-sections and in addition large fluxes of deuterium and tritium escaping from the plasma will strike the first walls. The question of hydrogen retention being enhanced by helium loading or radiation damage is of importance, particularly at higher temperatures. Of course, the payoff will be if retained hydrogen causes changes in mechanical properties.

As a first step, samples of aluminum, stainless steel, molybdenum and tantalum were implanted with deuterium both with and without prior helium implantations. For the helium loading, a 60 MeV α-particle beam from the cyclotron was degraded sufficiently to stop within the sample and due to straggling give a broad profile. A helium implant in a 1.2 mil aluminum foil was degraded to give a profile peaking at a depth of 0.5 mils as shown by the solid curve in Fig. 10. The degradation of the alpha beam was selected to give a profile peaking at 0.17 mils in a 0.6 mil stainless steel sample, see Fig. 11. A proton beam was not used as the hydrogen isotope implant because previous measurements (29) showed surface contamination of the order of micrograms of

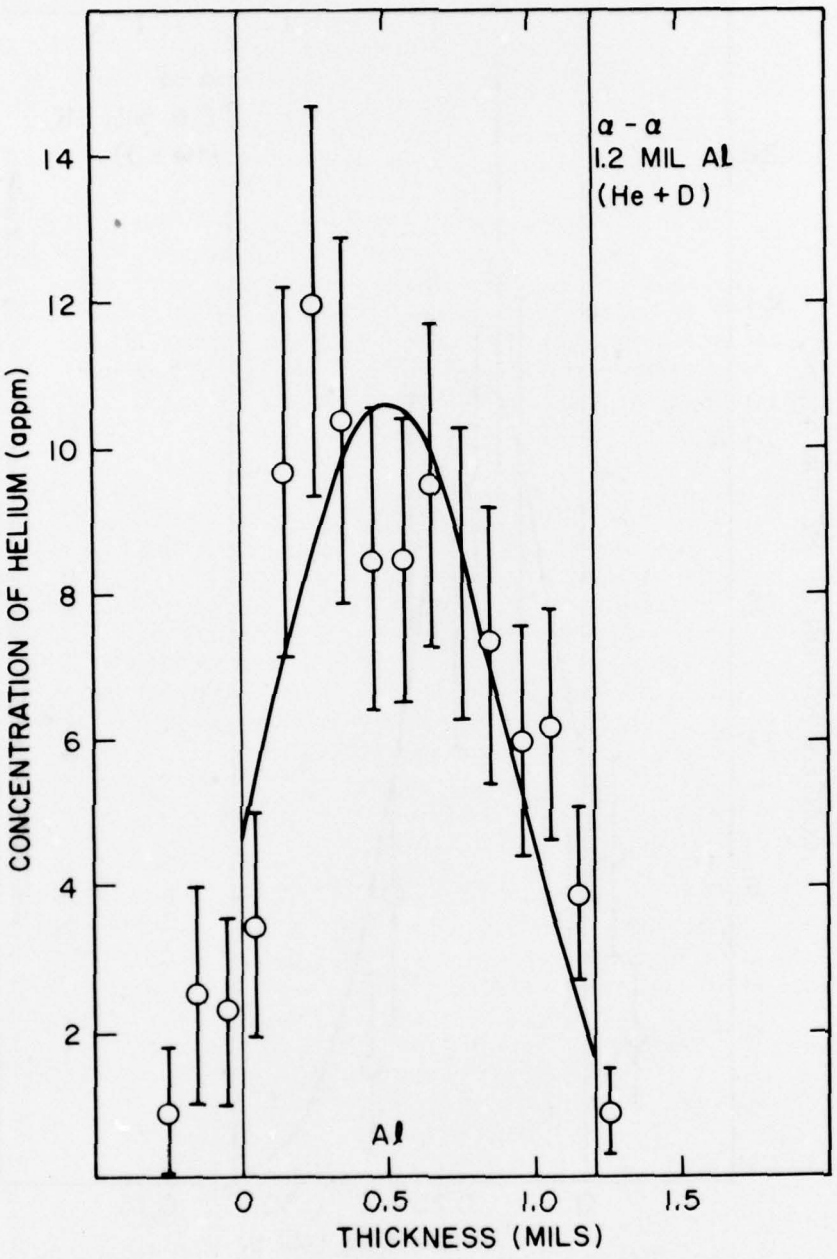


Fig. 10

Helium profile in a 1.2 mil aluminum sample implanted with helium and deuterium. The solid curve is the predicted implantation obtained from the computer code normalized by integrated current. The data points are from $\alpha - \alpha$ scattering when a 36.5 MeV alpha beam impinges on the sample.

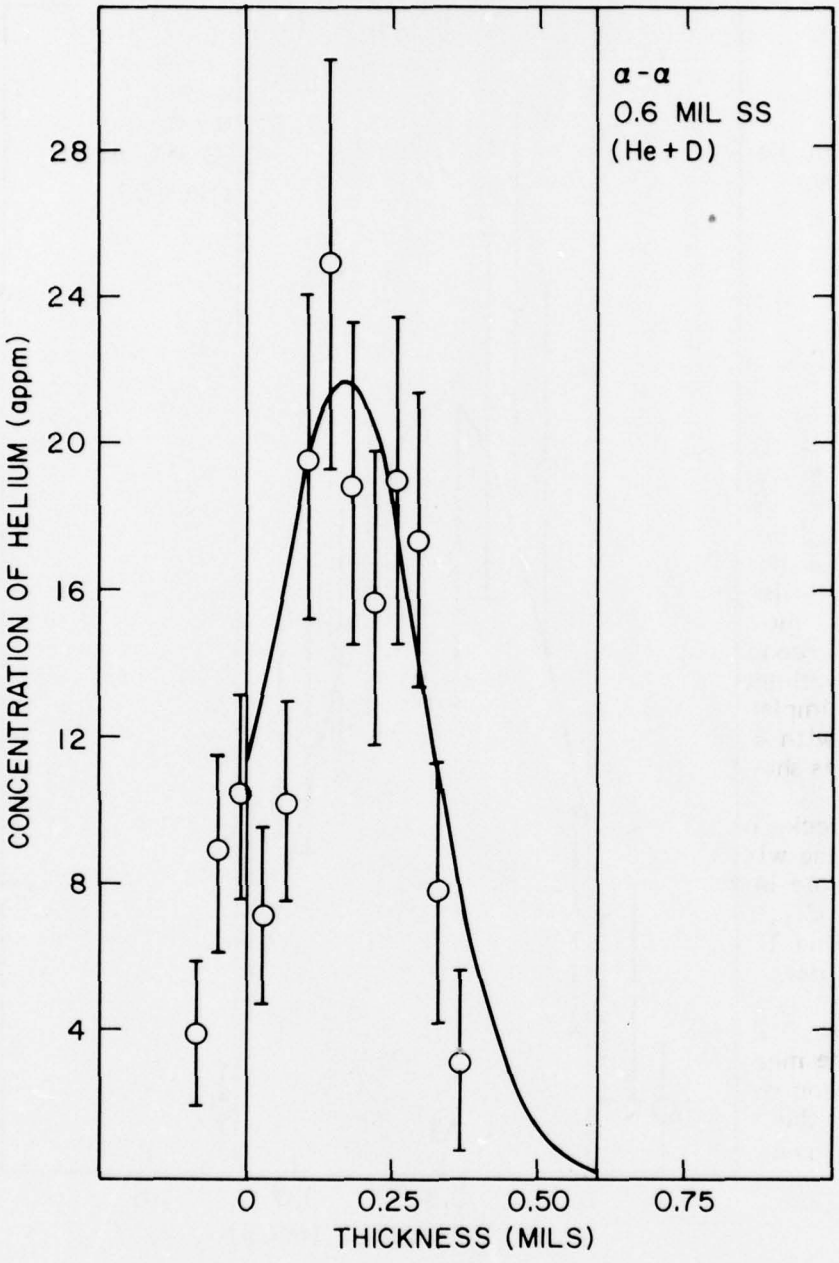


Fig. 11

Helium profile in a 0.6 mil stainless steel sample implanted with both helium and deuterium as in Fig. 1. The solid curve is the predicted helium profile.

hydrogen per cm^2 complicate hydrogen profiling by p-p elastic scattering. A 22.5 MeV deuteron beam was similarly degraded to give deuteron profiles peaking at the same depths in aluminum and stainless steel. The molybdenum (2.0 mils) and tantalum (1.0 mil) were similarly loaded but these specimens were too thick to profile at the loadings. The predicted profiles are obtained from a computer code written by Pieper that gives implantation concentrations in atomic parts per million (appm) per microcouloumb of implantation beam.

The loadings of two aluminum and two stainless steel specimens are shown in Table 3. *Helium and deuterium profiles* were measured by scattering with a 36.5 MeV alpha beam and by d-d scattering of a 22.5 MeV deuteron beam, respectively. A measured helium profile of the Al sample implanted with both α's and d's is shown in Fig. 10 in reasonable agreement with the predicted profile normalized by the integrated current during helium implantation. Due to the low implantation levels, statistics are poor and accidental backgrounds from host scatteirngs generated problems. The deuteron profile for this same aluminum sample is shown in Fig. 12 along with the predicted profile. The deuteron profile for the aluminum sample not preloaded with helium is similar and agrees well with the predicted loading indicating that the deuterium is being retained in aluminum under both conditions. In the stainless steel specimens, the measured helium profile as shown in Fig. 11 agrees reasonably well with the predicted peak. However, the deuteron profiles of the two stainless steel samples are different. The peak concentration of the deuteron profile measured in case of a 0.6 mil thick specimen previously loaded with helium agrees well with the predicted damage implant as seen in Fig. 13. The profile of deuterium in the sample not loaded with helium was not very statistically significant above background effects as shown in Fig. 14.

Checks of solid angles, alignment of the apparatus and depth resolutions were made with standard helium implanted samples, both surfaces implants and mid-sample implants. Similar checks were made for the deuterium profiles by use of a CD_2 target 5 μm thick and with similar CD_2 specimens placed in front and behind the aluminum and stainless steel samples. The surface specimens provide data to correct for multiple scattering effects occurring after the primary elastic event.

The measured peak values of the respective profiles are shown in Table 3 in comparison with the predicted implanted values. While a significant difference between the behavior of aluminum and stainless steel is evident, the experiment will be repeated with implants at least an order of magnitude higher dosages.

TABLE 3

PEAK CONCENTRATIONS OF IMPLANTED AND MEASURED PROFILES

Material	Thickness (Mils)	Implanted (appm) He	Implanted (appm) d	Measured (appm) He	Measured (appm) d
Al	1.2	12	6	10±3	5±1
Al	1.2	0	7	-	6.5±2.5
ss	0.6	22	10	20±5	10±3
ss	0.6	0	12	-	<4

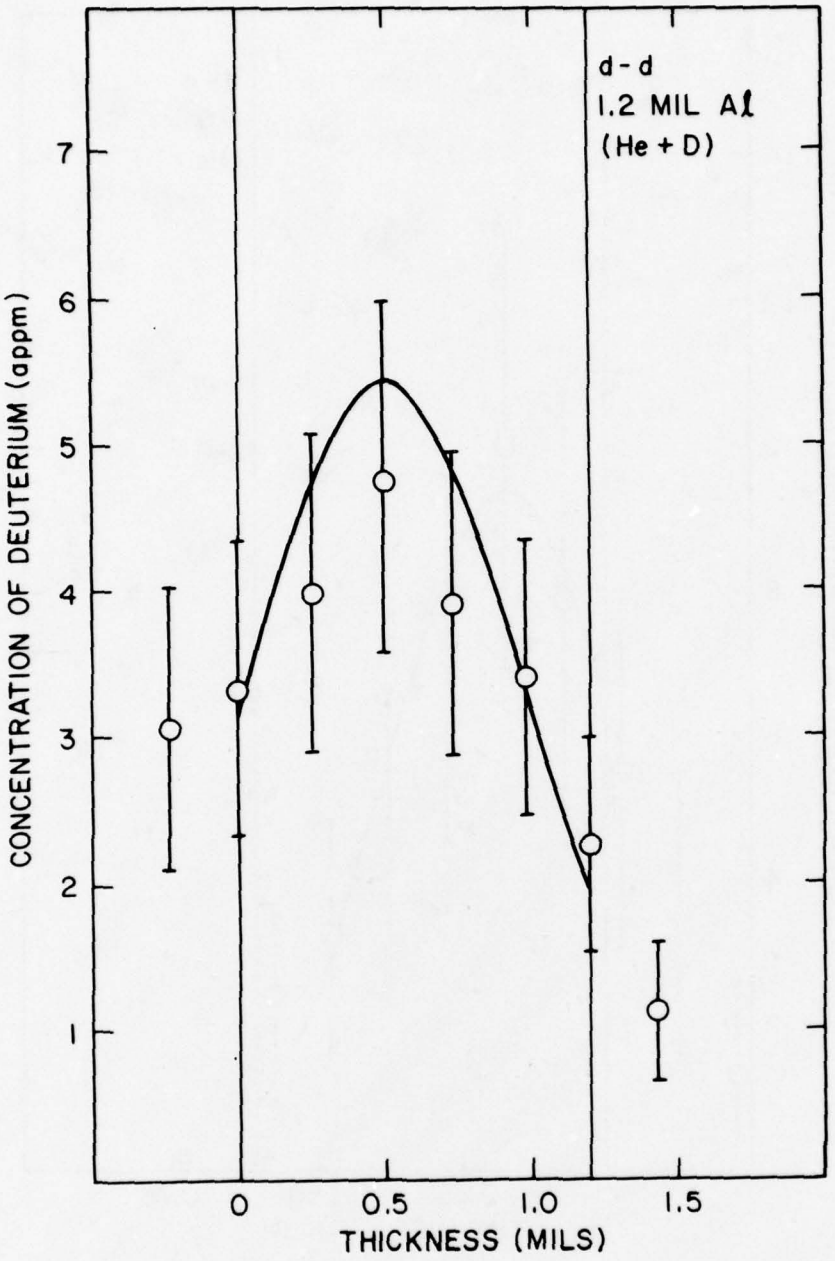


Fig. 12

Deuterium profile for the 1.2 mil aluminum sample implanted with helium and deuterium as measured by d-d scattering of a 22.5 MeV deuteron base. The solid curve is the predicted deuterium profile.

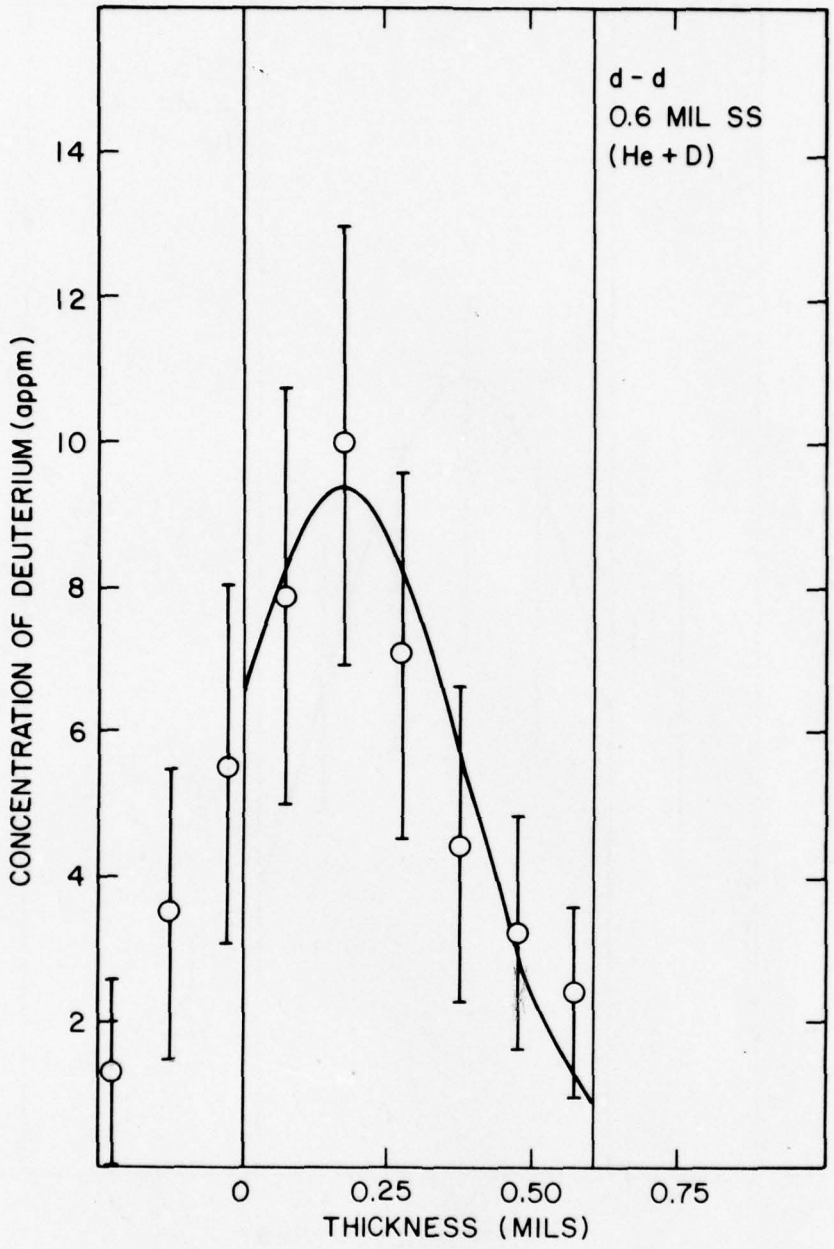


Fig. 13

Deuterium profile for the 0.6 mil stainless steel sample implanted with both helium and deuterium with the predicted curve.

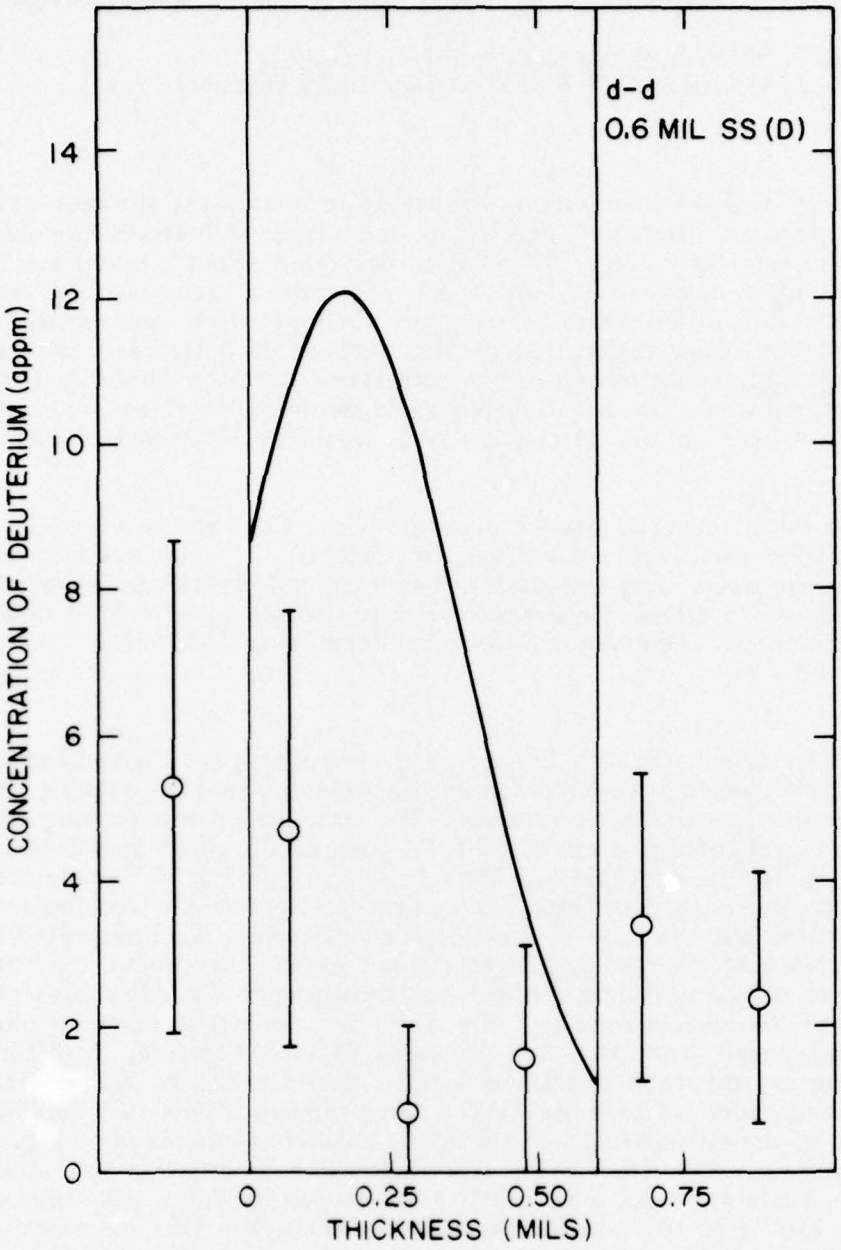


Fig. 14

Results of a deuterium profile of the 0.6 mil stainless steel sample implanted with only deuterium compared with the predicted curve.

B. X-ray Diffraction Measurements of Low-Level Radiation Damage

(L. S. Birks, J. W. Sandelin, and D. B. Brown
X-ray Optics Branch, Radiation Technology Division)

Background

1. It is well documented in the literature that x-ray diffraction can be used to measure dislocation density in crystals and therefore should be useful in measuring early stages of radiation damage in reactor materials. We proposed that alloy compositions which are resistant to void swelling might show different diffraction characteristics than alloys which are sensitive to void swelling (viz, lower dislocation density because of better recombination of interstitials and vacancies). If such a correlation could be established, then x-ray diffraction would be an effective rapid screening method for testing proposed alloys because the irradiation time would be reduced by orders of magnitude.

For the initial experiments we planned to use Cu crystals with selected low-concentration additives whose specific effects on void swelling have already been reported. Single-crystal rather than polycrystalline material is preferred because it allows more accurate x-ray measurements in a double-crystal spectrometer. The crystals were to be prepared by Code 5220.

Progress

Results to date have been limited to a crystal of pure Cu because it is the only specimen which has been prepared. Figure 15a shows the rocking curve obtained for that specimen as received. The area under the rocking curve (called the integral reflection coefficient, R) corresponds to an initial dislocation density of $<10^6/cm^2$, Table 4. After irradiation by 2×10^{-2} coulombs of 3.6 MeV alpha particles, Fig. 15b, the central portion of the rocking curve seems unaffected but the base is broadened considerably. We interpreted this as an indication that the damaged layer did not extend throughout the region contributing to the x-ray diffraction and that the curve of Fig. 15b represents a combination of the narrow rocking curve from the undamaged material plus a broad rocking curve from the thin damaged layer. Therefore, a different portion of the crystal was irradiated with a graded series of alpha-particle energies ranging from 1.2 to 4 MeV and a total fluence of 2×10^{-2} coulombs. This resulted in the curve of Fig. 15c which is broadened compared to Fig. 15a but retains a nearly Gaaussian shape. The dislocation density has increased to $3 \times 10^7/cm^2$, Table 4. Next, a second irradiation was added to the same area as for Fig. 15c (2×10^{-2} coulombs, graded energy). This increased the dislocation density, Table 4, and resulted in the rocking curve of Fig. 15d.

When dislocation density is plotted vs irradiation in Fig. 16 it appears that the damage increases at a faster than linear rate with irradiation initially but that it is beginning to approach a linear rate after $0.04\ C/cm^2$.

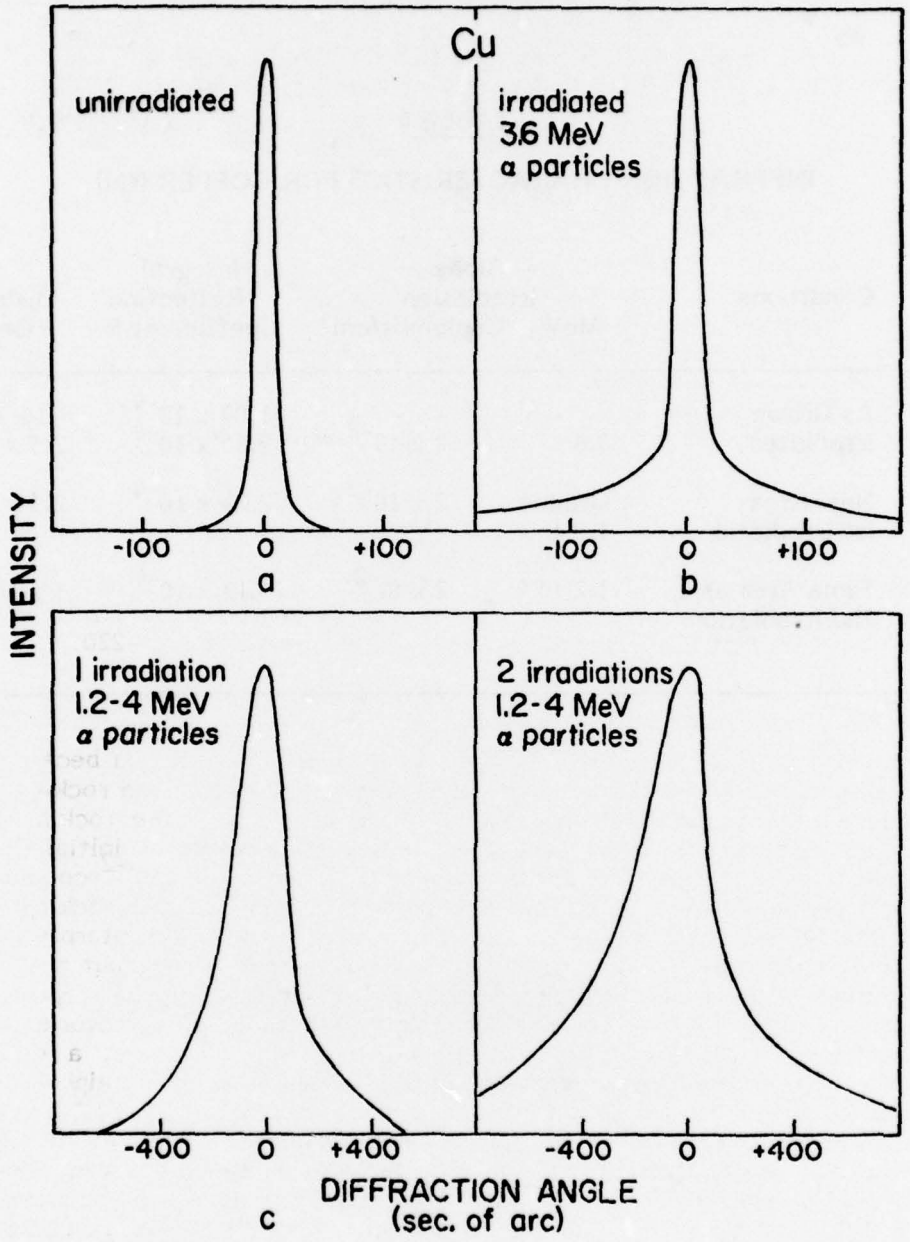


Fig. 15

Rocking curves for Cu single crystal. Irradiation with alpha particles of a single energy (b) broadens the base of the curve but alters the central peak only slightly. Irradiation with alpha particles of graded energies broadens the whole rocking curve (c and d).

TABLE 4

DIFFRACTION CHARACTERISTICS FOR COPPER (Cu)

Run	Conditions	Alpha Irradiation MeV	Alpha Irradiation Coulombs/cm^2	Integral Reflection Coefficient,R	Dislocation Density
a	As Grown	-	-	1.03×10^{-4}	$< 10^6/cm^2$
b	Irradiated	3.6	2×10^{-2}	2.65×10^{-4}	2.5×10^7
c	New Area 1st Irradiation	Graded 1.2 to 4	2×10^{-2}	2.74×10^{-4}	2.5×10^7
d	Same Area as c, 2nd Irradiation	1.2 to 4	2×10^{-2}	5.17×10^{-4}	3×10^8

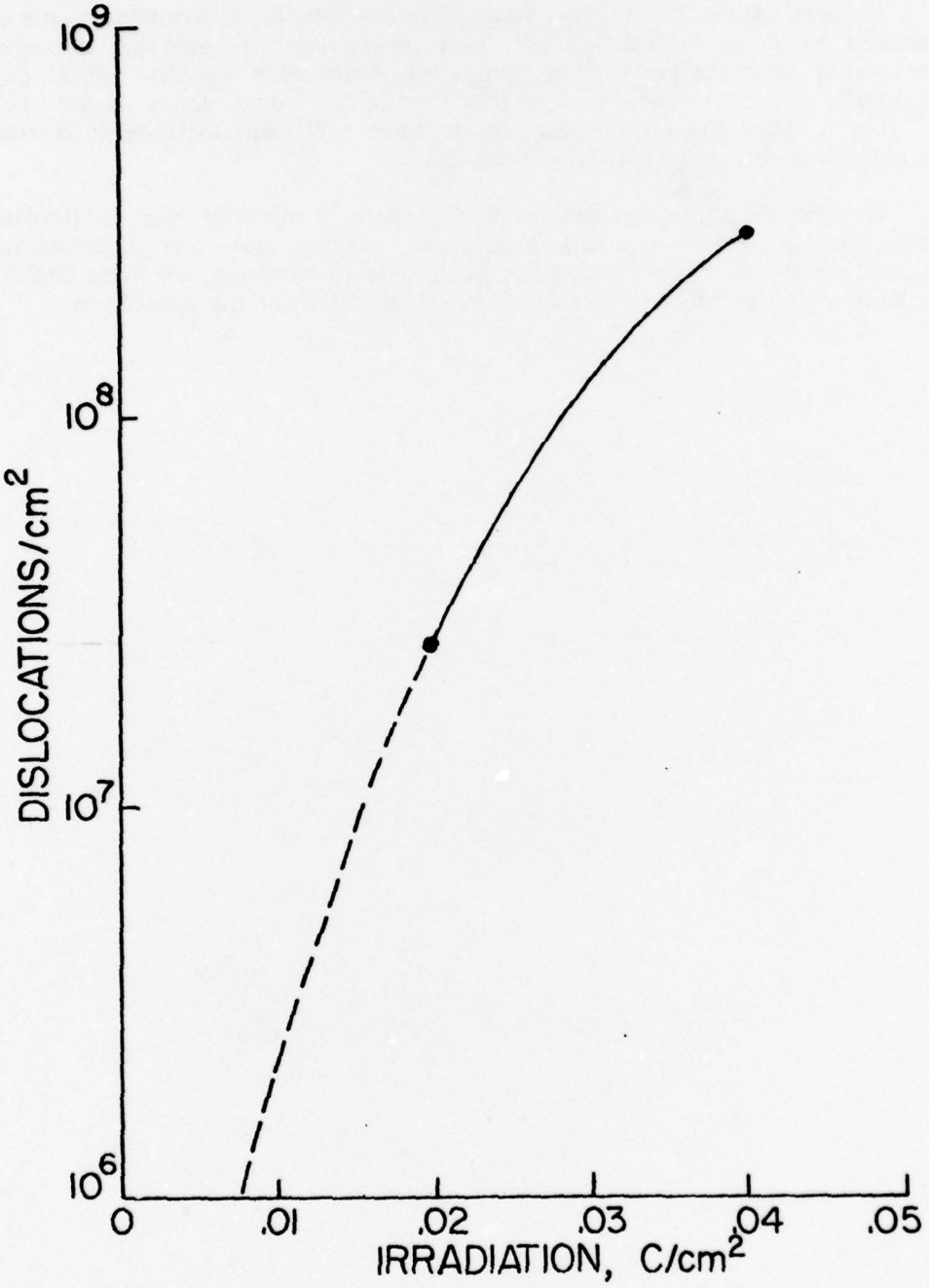


Fig. 16

Dislocation density as determined from x-ray rocking curves versus irradiation by alpha particles.

Conclusions

Results of the Cu crystal show that low levels of irradiation are easily observed by x-ray diffraction and that increments of radiation damage are measurable quantitatively. The limits of dislocation density which can be measured with the x-ray apparatus available range from about 10^6 to $10^{10}/cm^2$. Thus the method appears to have sufficient latitude to distinguish the effects of alloying additions to the Cu.

On the discouraging side of the picture it appears that difficulties in production of single crystals precludes carrying out the experiments as originally planned. Therefore, if the project is to continue, we must find a way to utilize polycrystalline material or go outside NRL for the specimens.

REFERENCES

1. J. F. Gibbons, W. S. Johnson, and S. W. Mylroie, Projected Range Statistics, The Halsted Press, 1975.

2. J. Lindhard, M. Scharff, and H. E. Schiott, Mat. Fys. Medd. 33, No. 14 (1963).

3. See for example, reference 4.

4. I. Manning and G. P. Mueller, Computer Phys. Commun. 7, 85 (1974).

5. J. Lindhard, V. Nielsen, M. Scharff, and P. V. Thomsen, Mat.-Fys. Medd. 33, No. 10 (1963).

6. G. L. Kulcinski, J. J. Laidler, and D. G. Doran, Radiation Effects 7, 195 (1971).

7. W. G. Johnston, J. H. Rosalowski, A. M. Turkalo, and T. Lauritzen, J. Nucl. Mater. 47, 155 (1973).

8. A. D. Marwick, J. Nucl. Mater. 55, 259 (1975).

9. M. D. Matthews, Radiation Effects 30, 61 (1976).

10. D. K. Brice, J. Appl. Phy. 46, 3385 (1975).

11. I. Manning, "Use of Range Distributions to Approximate Energy Distributions," Section I-A in this report.

12. F. A. Smidt, Jr., J. A. Sprague, J. E. Westmoreland, and P. R. Malmberg, Swelling in Dilute Binary Nickel Alloys," in Cooperative Radiation Effects Simulation Program, Semiannual Progress Report for the Period, 1 May to 31 October 1974 (L. E. Steele and E. A. Wolicki, Coordinators), NRL Memorandum Report 2998, March 1975, pp. 39-51.

13. F. A. Smidt, Jr., J. R. Reed, and J. A. Sprague, "A Comparison of the Swelling Produced in Nickel by Neutron Irradiation and by Ion Bombardment," in Radiation Effects in Breeder Reactor Structural Materials, (M. L. Bleiberg and J. W. Bennett, Eds.), The Metallurgical Society of AIME, 1977), pp. 377-386.

14. J. A. Sprague, J. E. Westmoreland, F. A. Smidt, Jr., and P. R. Malmberg, "The Temperature Dependence of Nickel-Ion Damage in Nickel," J. Nucl. Mater., 54, 286-278 (1974).

15. D. I. Potter, L. E. Rehn, P. R. Okamoto, and H. Wiedersich, "Void Swelling and Segregation in Dilute Nickel Alloys," in Radiation Effects in Breeder Reactor Structural Materials (M. L. Bleiberg and J. W. Bennett, Eds.), The Metallurgical Society of AIME, 1977, pp. 377-386.

16. J. E. Deverall and H. E. Watson, "Temperature Control in Irradiation Experiments with Gas-Controlled Heat Pipes," Proc. ANS Topical Meeting on Irradiation Experimentation in Fast Reactors, American Nuclear Society (1973), p.267.

17. J. Bentley and F. W. Wiffen, "Neutron Irradiation Effects in Molybdenum and Molybdenum Alloys," Technology of Controlled Nuclear Fusion, CONF-760935-P1 (1976), p. 209.

18. V. K. Sikka and J. Moteff, J. Nucl. Mater. 54, 325 (1974).

19. J. Bentley, B. L. Eyre, and M. H. Lorreto, "Suppression of Void Formation in Neutron Irradiated TZM," in Radiation Effects and Tritium Technology for Fusion Reactors, CONF-750989 (1976), p. I-297.

20. D. J. Michel and J. Moteff, "Voids in Neutron Irradiated and Annealed Niobium and Niobium-1% Zirconium Alloy," Rad. Effects, 21, 235 (1974).

21. H. Jang and J. Moteff, "The Influence of Neutron Irradiation Temperature on the Void Characteristics of Niobium and Niobium-1% Zirconium Alloys," in Radiation Effects and Tritium Technology for Fusion Reactors, CONF-750989 (1976), p. I-106.

22. B. A. Loomis, A. Taylor, S. B. Gerber, "Void Swelling of Nb and Nb-1% Zr Induced by Ni Bombardment," J. Nucl. Mater. 56, 25 (1975).

23. J. Bentley and F. W. Wiffen, "Swelling and Microstructural Changes in Irradiated Vanadium Alloys," Nucl. Technology 30, 376 (1976).

24. R. Carlander, S. D. Harkness, and A. T. Santhanam, "Effects of Fast Neutron Irradiation on Tensile Properties and Swelling Behavior of Vanadium Alloys," in Effects of Radiation on Substructure and Mechanical Properties of Metals and Alloys, ASTM STP 529, American Society for Testing and Materials, 1973, p. 399.

25. J. O. Stiegler, "Void Formation in Neutron-Irradiated Metals," in Radiation-Induced Voids in Metals, AEC Symposium Series, 26, 292 (1972).

26. W. A. Lanford, H. P. Trautvetter, J. F. Zeigler and J. Keller, Applied Physics Letters, 28, (No. 9), 566 (May 1976).

27. R. S. Nowicki, Vacuum Science Technology 14, (No. 1) 127 (January 1977).

28. S. T. Picraux, J. Bottiger and N. Reed, J. Nucl. Mater. 63, 110 (1976); Applied Physics Letters 28, (No. 4), 179 (1976).

29. L. A. Beach, A. G. Pieper, and J. E. Westmoreland, in Cooperative Radiation Effects Simulation Program, Semiannual Progress Report for Period, 1 Sep 1976 to 28 Feb 1977, NRL Memorandum Report 3588, Sept 1977, p. 23.

TECHNICAL PRODUCTIVITY

Publications

1. C. Z. Serpan, Jr. and H. H. Smith, "Fatigue Properties of Stainless Steel after Cyclotron Injection of Helium," Report of NRL Progress, pp. 17-19, December 1971.

2. L. E. Steele and E. A. Wolicki, Coordinators, "Cooperative Radiation Effects Simulation Program, Semiannual Progress Report, 1 May - 31 October 1971," NRL Memorandum Report 2394, February 1972.

3. C. Z. Serpan, Jr., H. H. Smith and A. G. Pieper, "Cyclotron Simulation of Helium Transmutation Damage in 304 Stainless Steel," Irradiation Effects on Reactor Structural Materials, QPR, 1 November 1971 - 31 January 1972, NRL Memorandum Report 2398, pp. 31-36, February 15, 1972.

4. H. H. Smith and C. Z. Serpan, Jr., "Fatigue Properties of Stainless Steel after Cyclotron Injection of Helium," Report of NRL Progress, pp. 25-26, April 1972.

5. H. H. Smith, C. Z. Serpan, Jr. and A. G. Pieper, "Effect of Cyclotron-Injected Helium on the Fatigue Properties of 316 Stainless Steel," Irradiation Effects on Reactor Structural Materials, QPR, 1 Feburary - 30 April 1972, NRL Memorandum Report, 2441, pp. 33-37, May 15, 1972.

6. C. Z. Serpan, Jr., H. H. Smith and A. G. Pieper, "Effect of Cyclotron-Injected Helium on Fatigue Characteristics of Stainless Steel," Trans. Amer. Nucl. Soc. 15:251, June 1972.

7. L. E. Steele and E. A. Wolicki, Coordinators "Cooperative Radiation Effects Simulation Program, Semiannual Progress Report, 1 November 1971 - 30 April 1972," NRL Memorandum Report 2484, August, 1972.

8. F. A. Smidt, Jr., J. A. Sprague, J. E. Westmoreland, P. R. Malmberg and I. Manning, "Heavy Ion Damage Studies," Irradiation Effects on Reactor Structural Materials, QPR, 1 May - 31 July 1972, NRL Memorandum Report 2505, pp. 5-13, August 15, 1972.

9. C. Z. Serpan, Jr., H. H. Smith and A. G. Pieper, "Fatigue Crack Growth in Helium-Implanted, Annealed and Cold Worked 316 Stainless Steel," Irradiation Effects on Reactor Structural Materials, QPR, 1 May - 31 July 1972, NRL Memorandum Report 2505, pp. 5-13, August 15, 1972.

10. J. A. Sprague, F. A. Smidt, J. E. Westmoreland and P.R. Malmberg, "Electron Microscopy Observations of Voids in Nickel-Ion Bombarded Nickel," Report of NRL Progress, pp.16-17, August 1972.

11. C. Z. Serpan, Jr., H. H. Smith, F. A. Smidt, and A. G. Pieper, "Fatigue Crack Growth at Elevated Temperatures in Helium Implanted Stainless Steel," Report of NRL Progress, pp. 17-19, October 1972.

12. C. Z. Serpan, Jr., H. H. Smith and A. G. Pieper, "Fatigue Crack Growth in Helium-Implanted, Annealed and Cold-Worked Type 316 Stainless Steel," Trans. Amer. Nucl. Soc. 15:721, November 1972.

13. F. A. Smidt, Jr. and A. G. Pieper, "Observations of Helium Bubble Growth in Cyclotron Implanted Type 316 Stainless Steel," Trans. Amer. Nucl. Soc. 15:722, November 1972.

14. C. Z. Serpan, Jr., H. H. Smith, F. A. Smidt, Jr. and A. G. Pieper, "Elevated-Temperature Fatigue Characteristics of Helium-Implanted Stainless Steel," Proceedings of International Meeting on Technology of Controlled Thermonuclear Fusion Experiments," Austin, Texas, 20-22 November 1972. (CONF-721111), Technical Information Center, Office of Information Services, AEC: pp. 993-1008, April 1974.

15. F. A. Smidt, Jr. and J. A. Sprague, "A Model for Vacancy Trapping by Impurities in Irradiated Iron," Report of NRL Progress, pp. 37-39, November 1972.

16. F. A. Smidt, Jr. and J. A. Sprague, "A Parametric Study of the Vacancy Trapping During Irradiation," Irradiation-Effects on Reactor Structural Materials, QPR, 1 August-31 October 1972. NRL Memorandum Report 2531, pp. 30-38, November 15, 1972.

17. C. Z. Serpan, Jr., H. H. Smith and A. G. Pieper, "Fatigue Crack Growth in Helium-Implanted Nb-1Zr Alloy," Report of NRL Progress, pp. 29-31, December 1972.

18. L. E. Steele and E. A. Wolicki, Coordinators "Cooperative Radiation Effects Simulation Program, Semiannual Progress Report, 1 May - 31 October 1972," NRL Memorandum Report 2555, February 1973.

19. H. H. Smith, C. Z. Serpan, Jr. and A. G. Pieper, "Fatigue Properties of Stainless Steel after Cyclotron Injection of Helium," Navy Materials Bulletin, VII (No. 1):10, February 1973.

20. J. A. Sprague, F. A. Smidt, Jr., J. E. Westmoreland and P. R. Malmberg, "The Effect of Ion-Beam Scanning on the Microstructure of Nickel-Ion Bombarded Nickel," Report of NRL Progress, pp. 45-47, February 1973.

21. C. Z. Serpan, Jr., H. H. Smith and A. G. Pieper, "Fatigue Life of Helium-Implanted TZM Alloy at Elevated Temperature," Report of NRL Progress, pp. 46-48, March 1973.

22. F. A. Smidt, Jr., A. G. Pieper and J. A. Sprague, "Observations of Bubble Growth in 316 Stainless Steel Implanted with Helium," Irradiation Effects on Reactor Structural Materials, QPR, 1 November 1972 - 31 January 1973, NRL Memorandum Report 2560, pp. 19-30, February 15, 1973.

23. C. Z. Serpan, Jr., H. H. Smith, D. J. Michel and A. G. Pieper, "Influence of Cyclotron-Injected Helium on the Fatigue Properties of 316 Stainless Steel," IBID, pp. 31-38.

24. C. Z. Serpan, Jr., D. J. Michel, H. H. Smith and A. G. Pieper, "Effect of Implanted Helium on Fatigue Behavior of TZM Alloys," Irradiation Effects on Reactor Structural Materials, QPR, 1 February - 30 April 1973, NRL Memorandum Report 2595, pp. 3-5, May 15, 1973.

25. J. A. Sprague, F. A. Smidt, Jr., J. E. Westmoreland and P. R. Malmberg, "The Effect of Beam Scanning on the Microstructure of Nickel-Ion Bombarded Nickel," IBID, pp. 37-46.

26. F. A. Smidt, Jr., J. A. Sprague and A. G. Pieper, "Observations of Helium Bubble Formation in 316 Stainless Steel," Report of NRL Progress, pp. 25-28, May 1973.

27. J. A. Sprague, J. E. Westmoreland, F. A. Smidt, Jr. and P. R. Malmberg, "The Effect of Beam Scanning on Nickel-Ion Damage in Nickel," Trans. Amer. Nucl. Soc. 16 (No. 1):70, 1973.

28. C. Z. Serpan, Jr., D. J. Michel, H. H. Smith and A. G. Pieper, "Microstructural Effects of Implanted Helium on Fatigue of 316 Stainless Steel," Trans. Amer. Nucl. Soc. 16 (No. 1):71, 1973.

29. F. A. Smidt, Jr. and J. A. Sprague, "Suppression of Void Nucleation by a Vacancy Trapping Mechanism," Scripta Met. 7:495, 1973.

30. F. A. Smidt, Jr., J. A. Sprague, J. E. Westmoreland and P. R. Malmberg, "The Effect of Alloy Additions on Void Nucleation and Growth," in Defects and Defect Clusters in BCC Metals and Their Alloys, R. J. Arsenault, ed., National Bureau of Standards, Gaithersburg, Maryland, 1973.

31. L. E. Steele and E. A. Wolicki, Coordinators, "Cooperative Radiation Effects Simulation Program, Semiannual Progress Report, 1 November 1972 - 30 April 1973, "NRL Memorandum Report 2629, August 1973.

32. J. A. Sprague and F. A. Smidt, Jr., "An Interferometric Electropolisher for Preparing Electron Microscopy Specimens of Heavy-Ion Bombarded Metals, Report of NRL Progress, pp. 35-37, August 1973.

33. I. Manning and D. W. Padgett, "Transport Theory of Penetration by Heavy Ions," NRL Memorandum Report 2631, August 1973.

34. F. A. Smidt, Jr. and J. A. Sprague, "Comments on the Suppression of Void Nucleation by Oversize Solute Atoms," Scripta Met. 7 (#10):1065, 1973.

35. F. A. Smidt, Jr., J. A. Sprague, J. E. Westmoreland and P. R. Malmberg, "Observations of Damage Produced in Iron and Iron Alloys by Neutron Irradiation and Ion Bombardment," Irradiation Effects on Reactor Structural Materials, 1 May - 31 July 1973, NRL Memorandum Report 2639, pp. 20-30, August 15, 1973.

36. D. J. Michel and C. Z. Serpan, Jr., "Microstructure of Helium-Implanted Annealed and Cold Worked 316 Stainless Steel Aged at 650°C, "Irradiation Effects on Reactor Structural Materials, 1 May - 31 July 1973, NRL Memorandum Report 2639, pp. 30-34, August 15, 1973.

37. J. E. Westmoreland, J. A. Sprague, F. A. Smidt and P. R. Malmberg, "Flux (Dose Rate) Effects for 2.8 MeV ^{58}Ni Irradiations of Pure Ni," Applications of Ion Beams to Metals, S. T. Picraux E. P. EerNisse and F. L. Vook, eds., Plenum Press, New York, (1974), p. 663.

38. H. H. Smith, D. J. Michel and A. G. Pieper, "Fatigue Life of Helium Implanted Type 316 Stainless Steel at 650°C," Report of NRL Progress, pp. 37-38, October 1973.

39. D. J. Michel, C. Z. Serpan, Jr., H. H. Smith and A. G. Pieper, "Effect of Cyclotron Implanted Helium on the Fatigue Behavior and Microstructure of 316 Stainless Steel at 650°C," Proceedings of Symposium on Engineering Problems of Fusion Research, Princeton University, pp. 49-53, 6-9 November 1973.

40. C. Z. Serpan, Jr., H. H. Smith, F. A. Smidt, Jr. and A. G. Pieper, "Elevated Temperature Fatigue Characteristics of Helium-Implanted Stainless Steel," AEC Symposium Series 31, pp. 993-1008 (April 1974); Proceedings of International Meeting on Technology of Controlled Thermonuclear Reactors, 20-22 November 1973.

41. F. A. Smidt, Jr., "Evaluation of Heavy Ion Bombardment Techniques for the Study of Void Formation," Navy Materials Bulletin, VII (No. 3):29, November 1973.

42. F. A. Smidt, Jr., J. A. Sprague, J. E. Westmoreland and P. R. Malmberg, "The Effect of 0.3 at-% Solute Additions on Void Nucleation," Report of NRL Progress, pp. 36-38, November 1973.

43. D. J. Michel, C. Z. Serpan, Jr., H. H. Smith and A. G. Pieper, "Effect of Helium on Fatigue Behavior of the Molybdenum-Base-Alloy TZM," Trans. Amer. Nucl. Soc. 17:144, November 1973.

44. G. P. Mueller, "Application of Jacobi Polynomial Methods to the One-Speed Transport Equation," Radiation Effects 20, 229, 1973.

45. D. J. Michel, H. H. Smith, C. Z. Serpan, Jr., H. E. Watson and A. G. Pieper, "The Effect of Microstructure on the Fatigue Life of Helium-Implanted TZM Alloy," Report of NRL Progress, pp. 52-54, January 1974.

46. L. E. Steele and E. A Wolicki, Coordinators, "Cooperative Radiation Effects Simulation Program, Semiannual Progress Report for the Period 1 May 1973 - 31 October 1973," NRL Memorandum Report 2755, February 1974.

47. F. A. Smidt, Jr., J. A. Sprague and A. G. Pieper, "Studies of the Mobility of He in V," Report of NRL Progress, pp. 24-27, February 1974.

48. J. A. Sprague, F. A. Smidt, Jr., J. E. Westmoreland and P. R. Malmberg, "The Temperature and Dose Rate Dependence of Void Nucleation and Growth in Heavy Ion Bombarded Nickel," Irradiation Effects on Reactor Structural Materials, 1 August 1973-31 January 1974, NRL Memorandum Report 2752, pp. 22-40, March 1974.

49. F. A. Smidt, Jr. and A. G. Pieper, "Studies of the Mobility of Helium in Vanadium," Irradiation Effects on Reactor Structural Materials, 1 August 1973 - 31 January 1974, NRL Memorandum Report 2752, pp. 41-49, March 1974.

50. H. H. Smith, D. J. Michel and A. G. Pieper, "Fatigue of Cyclotron Implanted Helium on the Fatigue Behavior of 316 Stainless Steel at 650^{o}C," Irradiation Effects on Reactor Structural Materials, 1 August 1973 - 31 January 1974, NRL Memorandum Report 2752, pp. 49-54, March 1974.

51. D. J. Michel, C. Z. Serpan, Jr.,H. H. Smith and A. G. Pieper, "Effect of Helium on the Fatigue Behavior of the Molybdenum Base Alloy TZM at 900^{o}C," Nuclear Technology 22:79-87, April 1974.

52. L. E. Steele and E. A. Wolicki, Coordinators, "Cooperative Radiation Effects Simulation Program, Semiannual Progress Report for the Period 1 November 1973 - 30 April 1974," NRL Memorandum Report 2866, July 1974.

53. J. A. Sprague, F. A. Smidt, Jr., J. E. Westmoreland and P. R. Malmberg, "The Temperature Dependence of Nickel Ion Damage in Nickel," Report of NRL Progress, pp. 37-40, May 1974.

54. F. A. Smidt, Jr., J. A. Sprague and A. G. Pieper, "Observations of He Bubble Formation in 316 Stainless Steel," Report of NRL Progress, pp. 24-25, August 1974.

55. F. A. Smidt, Jr. and A. G. Pieper, "Studies of the Mobility of Helium in Vanadium," J. Nucl. Matl. 51:361, 1974.

56. J. A. Sprague, F. A. Smidt, Jr., J. E. Westmoreland and P. R. Malmberg, "The Dose Dependence of Nickel Ion Damage in Nickel," Irradiation Effects on Reactor Structural Materials, 1 February - 31 July 1974, NRL Memorandum Report 2875, pp. 39-48, August 1974.

57. F. A. Smidt, Jr. and A. G. Pieper, "Studies of the Mobility of Helium in 316 Stainless Steel and Aluminum," Irradiation Effects on Reactor Structural Materials, 1 February - 31 July 1974, NRL Memorandum Report 2875, pp. 48-59, August 1974.

58. J. E. Westmoreland, J. A. Sprague, F. A. Smidt, Jr. and P. R. Malmberg, "Dose-Rate Dependence of Irradiation Parameters in Nickel-Ion-Irradiated Nickel," Trans. Amer. Nucl. Soc. 19:149, 1974.

59. A. G. Pieper, L. S. August and F. A. Smidt, Jr., "Nondestructive Measurement of Helium Concentration in Metal Foils," Trans. Amer. Nucl. Soc. 19:125, 1974.

60. J. A. Sprague, J. E. Westmoreland, F. A. Smidt, Jr. and P. R. Malmberg, "The Temperature Dependence of Nickel-Ion Damage in Nickel," J. Nucl. Materials 54 (#2):286, 1974.

61. J. A. Sprague, J. E. Westmoreland, F. A. Smidt, Jr. and P. R. Malmberg, "The Determination of Void Formation Parameters in Metals by Heavy-Ion Irradiation," Proceedings of Symposium on the Physics of Irradiation-Produced Voids, Harwell, England, 9-11 September 1974; AERE-R-7934, p. 263, January 1975.

62. J. E. Westmoreland, J. A. Sprague, F. A. Smidt, Jr. and P. R. Malmberg, "Flux Dependence of Void Nucleation and Void Growth in 2.8 MeV Nickel-Ion-Irradiated Nickel," Proceedings of Symposium on the Physics of Irradiation-Produced Voids, Harwell, England, 9-11 September 1974; AERE-R-7934, p. 268, January 1975.

63. J. E. Westmoreland, P. R. Malmberg, J. A. Sprague, and F. A. Smidt, Jr., "Flux Dependence of Void Nucleation and Void Growth in 2.8-MeV Nickel-Ion-Irradiated Nickel," 21st National Symposium of the American Vacuum Society, JVST, 12, 511 (1975).

64. J. A. Sprague, J. E. Westmoreland, F. A. Smidt, Jr. and P. R. Malmberg, "Void Formation in Nickel-Ion-Irradiated Nickel," Proceedings of European Conference on Irradiation Behavior of Fuel Cladding and Core Component Materials, Karlsruhe, Germany, 3-5 December 1974.

65. F. A. Smidt, Jr., J. A. Sprague, J. E. Westmoreland and P. R. Malmberg, "The Influence of Minor Alloy Additions on Swelling," Proceedings of European Conference on Irradiation Behavior of Fuel Cladding and Core Component Materials, Karlsruhe, Germany, 3-5 December 1974.

66. F. A. Smidt, Jr., "Metals in High Temperature Nuclear Environments," Workshop on Light Weight Nuclear Power Plants, 22-25 October 1974, ONR-473-01-75, 14 January 1975.

67. J. A. Sprague, F. A. Smidt, Jr., J. E. Westmoreland and P. R. Malmberg, "Fluence Dependence of Ion Damage in Nickel," Irradiation Effects on Reactor Structural Materials, 1 August 1974 - 31 January 1975, NRL Memorandum Report 3010, pp. 21-30, February 1975.

68. J. E. Westmoreland and J. A. Sprague, "Physics of Irradiation-Produced Voids," ONR London Newsletter, European Scientific Notes, ESN-29-1, pp. 34-35, 31 January 1975..

69. P. L. Hendrick, D. J. Michel, A. G. Pieper, R. E. Surratt and A. L. Bement, "Ion-Simulated Irradiation Induced Creep of Reactor Structural Alloys," Irradiation Effects on Reactor Structural Materials, 1 August 1974 - 31 January 1975, NRL Memorandum Report 3010, p. 30, February 1975.

70. J. A. Sprague, F. A. Smidt, Jr., J. E. Westmoreland and P. R. Malmberg, "The Temperature Dependence of Nickel Ion Damage in Nickel," Report of NRL Progress, pp. 24-26, February 1975.

71. J. E. Westmoreland, P. R. Malmberg, J. A. Sprague and F. A. Smidt, Jr., "Dose Rate Effects in Nickel-Ion-Irradiated Nickel," Report of NRL Progress, pp. 45-46, February 1975.

72. G. P. Mueller and J. E. Westmoreland, "Modification of E-DEP-1 to Run for High Energy Helium Ions in Nickel and Type 316 Stainless Steel," NRL Memorandum Report 3019, March 1975.

73. J. A. Sprague, F. A. Smidt, Jr., J. E. Westmoreland and P. R. Malmberg, "The Temperature Dependence of Nickel Ion Damage in Nickel," Navy Materials Bulletin IX (#1):27, March 1975.

74. F. A. Smidt, "European Conference on Irradiation Behavior of of Fuel Cladding and Core Component Materials," ONR-London, Newsletter, European Scientific Notes, ESN-29-3, pp. 124-127, 31 March 1975.

75. L. E. Steele and E. A. Wolicki, Coordinators "Cooperative Radiation Effects Simulation Program, Semiannual Progress Report for the Period 1 May - 31 October 1974," NRL Memorandum Report 2998, March 1975.

76. J. A. Sprague, F. A. Smidt, Jr., J. E. Westmoreland and P. R. Malmberg, "Fluence Dependence of Swelling in Ion-Irradiated Nickel," Report of NRL Progress, pp. 19-22, May 1975.

77. F. A. Smidt, Jr., J. A. Sprague, J. E. Westmoreland and P. R. Malmberg, "Effect of Alloy Additions on Swelling of Nickel," Report of NRL Progress, pp. 32-34, August 1975.

78. F. A. Smidt, Jr., J. A. Sprague and A. G. Pieper, "Observations of Helium Bubble Formation in 316 Stainless Steel," Report of NRL Progress, pp. 24-25, August 1974.

79. P. L. Hendrick, "Ion-Simulated Irradiation-Induced Creep," Ph.D. Thesis, Massachusetts Institute of Technology, August 7, 1975.

80. J. A. Sprague, "Diffraction Fine Structure and Contrast from Octahedral Voids in Nickel," 33rd Annual Proceedings, Electron Microscopy Society of America, Las Vegas, Nevada, 11-15 August 1975; (G. W. Bailey, ed.), 1975, pp. 162-163.

81. P. L. Hendrick, D. J. Michel, A. G. Pieper, R. E. Surratt and A. L. Bement, "Simulation of Irradiation-Induced Creep in Nickel," Irradiation Effects on Reactor Structural Materials, 1 February - 31 July 1975," NRL Memorandum Report 3110, pp. 9-22, August 1975.

82. F. A. Smidt, Jr., J. A. Sprague, J. E. Westmoreland and P. R. Malmberg, "Swelling in Dilute Binary Nickel Alloys," Irradiation Effects on Reactor Structural Materials, 1 February - 31 July 1975," NRL Memorandum Report 3110, pp. 33-45, August 1975.

83. P. L. Hendrick, et al., "Simulation of Creep in Nuclear Reactor Materials," NRL Research and Development Highlights, Vol. 2, No. 4, pp. 13-14, September 1975.

84. L. E. Steele and E. A. Wolicki, Coordinators "Cooperative Radiation Effects Simulation Program, Semiannual Progress Report for the Period 1 November 1974 - 30 April 1975," NRL Memorandum Report 3114, August 1975.

85. D. J. Michel, P. L. Hendrick, A. G. Pieper and R. E. Surratt, "Irradiation Induced Creep Microstructure of Nickel," Report of NRL Progress, pp. 6-8, October 1975.

86. J. A. Sprague, K. C. Russell and Y. H. Choi, "Evaluation of Time-Dependent Void Nucleation Theory Under Ion Bombardment Conditions," Proceedings of International Conference on Fundamental Aspects of Radiation Damage in Metals, Gatlinburg, Tennessee, pp. 1181-1187, 6-10 October 1975. Washington: U.S. Government Printing Office, 1976.

87. F. A. Smidt, Jr., J. A. Sprague, L. G. Kirchner, J. E. Westmoreland and P. R. Malmberg, "The Stability of Ni, Al Precipitates Under Heavy Ion Irradiation," Report of NRL Progress, pp. 17-19, November 1975.

88. J. E. Westmoreland, J. A. Sprague, F. A. Smidt, Jr. and P. R. Malmberg, "Dose Rate Effects in Nickel-Ion-Irradiated Nickel," Radiation Effects 26, 1 (1975).

89. I. Manning and G. P. Mueller, "Approximate Calculation of Energy Deposition in Ion Bombardment," The Physics of Irradiadiation Produced Voids, edited by R. S. Nelson, Harwell Report AERE-R7934, p. 37 (1975).

90. I. Manning and G. P. Mueller, "Computer Code for Depth Distribution of Energy Deposition by Heavy Ion Bombardment," Nuclear Engineering and Design 33, No. 1, 78 (1975).

91. G. P. Mueller and J. E. Westmoreland, "Extension of the Energy Deposition Code E-DEP-1 to Higher Energies," NRL Memorandum Report 3194, January 1976.

92. F. A. Smidt, Jr. and A. G. Pieper, "Helium Mobility and Bubble Formation in Type 316 Stainless Steel, Aluminum and Vanadium," Properties of Reactor Structural Alloys after Neutron or Particle Irradiation, ASTM STP 570, pp. 352-368, February 1976.

93. J. A. Sprague, J. E. Westmoreland, F. A. Smidt, Jr. and and P. R. Malmberg, "The Effect of Irradiation Parameters on Nickel-Ion Damage in Nickel," Properties of Reactor Structural Alloys after Neutron or Particle Irradiation, ASTM STP 570, pp. 505-522, February 1976, discussion, pp. 522-524.

94. F. A. Smidt, Jr. and A. G. Pieper, "Observations of Helium Bubble Formation in 316 Stainless Steel Implanted by Alpha Bombardment," Proceedings of International Conference on Radiation Effects and Tritium Technology for Fusion Reactors, Gatlinburg, Tennessee, 1-3 October 1975, Vol. II, pp. 250-279, March 1976. Springfield, Virginia: NTIS.

95. P. L. Hendrick, D. J. Michel, A. G. Pieper, R. E. Surratt and A. L. Bement, Jr.,"Ion-Simulated Irradiation-Induced Creep of Nickel," Proceedings of International Conference on Radiation Effects and Tritium Technology for Fusion Reactors, Gatlinburg, Tennessee, 1-3 October 1975, Vol. II, pp. 84-117, March 1976.

96. J. A. Sprague, F. A. Smidt, Jr., J. E. Westmoreland and P. R. Malmberg, "The Effect of Ion Irradiation on the Microsructure of an Fe-Ni-Cr Alloy," Report of NRL Progress, pp. 19-21, May 1976.

97. F. A. Smidt, Jr., Coordinator, "Controlled Thermonuclear Reactor Materials Program Annual Progress Report for the Period 1 January - 31 December 1975," NRL Memorandum Report 3293, May 1976.

98. L. E. Steele, ed., "Cooperative Radiation Effects Simulation Program, Semiannual Progress Report for the Period 1 May 1975 - 31 March 1976," NRL Memorandum Repoer 3312, June 1976.

99. G. P. Mueller, M. Rosen and I. Manning, "A Boltzmann Transport Code for Ions in Matter, "NRL Report of Progress, pp. 47-48, July 1976.

100. I. Manning, M. Rosen and J. E. Westmoreland, "Computer Code for the Calculation of Lateral Range of a PKA," NRL Memorandum Report 3358, September 1976.

101. F. A. Smidt, Jr., J. A. Sprague, P. R. Malmberg and J. E. Westmoreland, "Evaluation of Swelling in Ferritic Alloys EM-12 and HT-9 by Using Ion Bombardment," Report of NRL Progress, pp. 15-17, September 1976.

102. J. A. Sprague, F. A. Smidt, Jr., J. E. Westmoreland and P. R. Malmberg, "Effect of Ion Irradiation on the Microstructure of an Iron-Nickel-Chromium Alloy," Irradiation Effects on the Microstructure and Properties of Metals, ASTM STP 611, pp. 337-352, November 1976.

103. F. A. Smidt, Jr., P. R. Malmberg, J. A. Sprague and J. E. Westmoreland, "Swelling Behavior of Commercial Ferritic Alloys, EM-12 and HT-9, as Assessed by Heavy Ion Bombardment," Irradiation Effects on the Microstructure and Properties of Metals, ASTM STP 611, pp. 227-241, November 1976.

104. D. J. Michel, P. L. Hendrick and A. G. Pieper, "Microstructure and Mechanisms of Ion-Simulated Irradiation-Induced Creep of Nickel," Irradiation Effects on the Microstructure and Properties of Metals, ASTM STP 611, pp. 284-297, November 1976.

105. L. G. Kirchner, F. A. Smidt, Jr., G. L. Kulcinski, J. A. Sprague, J. E. and Westmoreland, "Nickel Ion Damage in Precipitation-Hardened Ni-Al," Irradiation Effects on the Microstructure and Properties of Metals, ASTM STP 611, pp. 370 - 384, November 1976.

106. J. A. Sprague and F. A. Smidt, Jr., "Measurement of Void Size by Transmission Electron Microscopy," Report of NRL Progress, pp. 26-30, December 1976.

107. P. L. Hendrick, D. J. Michel, A. G. Pieper, R. E. Surratt, and A. L. Bement, Jr., "Simulation of Irradiation-Induced Creep in Nickel," J. Nuclear Materials 59, pp. 229-233 (1976).

108. P. L. Hendrick, D. J. Michel, A. G. Pieper, R. E. Surratt and A. L. Bement, Jr., "Ion-Simulated Irradiation-Induced Creep," Nucl. Instr. and Methods 133, pp. 509-520 (1976).

109. F. A. Smidt, Jr., J. A. Sprague, et al., "Summary Report on the Alloy Development Intercorrelation Program Experiment," Proceedings of the Workshop on Correlation of Neutron and Charged Particle Damage, Oak Ridge National Laboratory, 8-10 June 1976 (1977); (CONF-760672) (HEDL-SA-874), Springfield, Virginia: NTIS.

110. J. L. Brimhall, et al., (F. A. Smidt, Jr., participant), "Summary Report on BCC Ion Correlation Experiment," Proceedings of the Workshop on Correlation of Neutron and Charged Particle Damage, Oak Ridge National Laboratory, 8-10 June 1976 (1977); (CONF-760672) (HEDL-SA-874), Springfield, Virginia: NTIS.

111. W. G. Johnston, N. H. Packan and F. A. Smidt, Jr., "Summary of Workshop Discussion," Proceedings of the Workshop on Correlation of Neutron and Charged Particle Damage, Oak Ridge National Laboratory, 8-10 June 1976 (1977); CONF-760672) (HEDL-SA-874), Springfield, Virginia: NTIS.

112. L. A. Beach and L. E. Steele, Coordinators "Cooperative Radiation Effects Simulation Program, Semiannual Progress Report for the Period 1 April - 31 August 1976," NRL Memorandum Report 3456, February 1977.

113. D. J. Michel, P. L. Hendrick and A. G. Pieper, "Transient Ion-Simulated Irradiation-Induced Creep of Nickel," Trans. ANS, Vol. 26, pp. 195-196, 1977.

114. J. A. Sprague, F. A. Smidt, Jr. and V. Provenzano, "Void and Bubble Size Measurement: The Effect of Focus Condition," Report of NRL Progress, pp. 6-8, May 1977.

115. G. P. Mueller and Mervine Rosen, "A Boltzmann Transport Code for Ion Penetration in Matter," NRL Memorandum Report 3556, July 1977.

116. F. A. Smidt, Jr., J. R. Reed, J. A. Sprague and V. Provenzano, "A Comparison of the Swelling Produced in Nickel by Neutron Irradiation and Ion Bombardment, Report of NRL Progress, pp. 2-6, August 1977.

117. L. E. Steele and L. A. Beach, Coordinators "Cooperative Radiation Effects Simulation Program, Semiannual Progress Report for the Period 1 September 1976 - 28 February 1977," NRL Memorandum Report 3588, September 1977.

118. G. P. Mueller and M. Rosen, "A Boltzmann Transport Code for Ion Penetration in Matter, Report of NRL Progress, pp. 23-24, September 1977.

119. G. P. Mueller, "Differential Cross Section and Related Integrals for the Moliere Potential," Report of NRL Progress, pp. 23-24, April 1978.

120. G. P. Mueller, "Differential Cross Section and Related Integrals for the Moliere Potential," NRL Report 8207, 12 May 1978.

121. D. J. Michel, P. L. Hendrick, and A. G. Pieper, "Transient Irradiation-Induced Creep of Nickel During Deuteron Bombardment," J. Nucl. Materials, 75:1, 1978.

122. L. E. Steele and L. A. Beach, Coordinators, "Cooperative Radiation Effects Simulation Program, Semiannual Progress Report for the Period 1 March 1977 - 31 August 1977," NRL Memorandum Report 3806, July 1978.

123. J. A. Sprague, K. B. Roarty, and V. Provenzano, "The Effect of Alloy Additions on the Swelling of Neutron-Irradiated Nickel," Report of NRL Progress, pp. 6-9, August 1978.

124. G. P. Mueller and M. Rosen, "Cubic Spline Solution to Integral Equations," NRL Memorandum Report 3942, 5 March 1979.

Presentations

1. C. Z. Serpan, Jr., H. H. Smith and A. G. Pieper, "Effects of Cyclotron-Injected Helium on Fatigue Characteristics of Stainless Steel," Amer. Nucl. Soc. Spring Meeting, Las Vegas, Nevada, June 1972; Trans. Amer. Nucl. Soc. 15:251, 1972.

2. C. Z. Serpan, Jr., "Radiation Damage and Helium Embrittlement in Elevated Temperature Reactor Structural Alloys," Los Alamos Scientific Laboratory, Los Alamos, New Mexico, 26 September 1972.

3. F. A. Smidt, Jr. and J. A. Sprague, "A Parametric Study of Vacancy Trapping in Irradiated Iron," Symposium on Diffusion in Systems of Nuclear Interest, AIME, The Metallurgical Society, Cleveland, Ohio, October 1972.

4. I. Manning and G. P. Mueller, "Computer Code for Depth Distribution of Energy Deposition by Heavy Ion Bombardment," Specialists Conference on Radiation Damage Units in Ferritic and Austenitic Stainless Steels, IAEA, Seattle, Washington, 31 October - 1 November 1972.

5. C. Z. Serpan, Jr., H. H. Smith and A. G. Pieper, "Fatigue Crack Growth in Helium-Implanted, Annealed and Cold-Worked 316 Stainless Steel," Amer. Nucl. Soc. Winter Meeting, Washington, D. C., 12-17 November 1972; Trans. Amer. Nucl. Soc. 15:721, 1972.

6. F. A. Smidt, Jr. and A. G. Pieper, "Observations of Helium Bubble Growth in Cyclotron Implanted 316 Stainless Steel," Amer. Nucl. Soc. Winter Meeting, WAshington, D. C., 12-17 November 1972; Trans. Amer. Nucl. Soc. 15:722, 1972.

7. C. Z. Serpan, Jr., H. H. Smith, F. A. Smidt, Jr. and A. G. Pieper, "Elevated-Temperature Fatigue Characteristics of Helium-Implanted Stainless Steel," International Meeting on Technology of Controlled Thermonuclear Fusion Experiments, Austin, Texas, 20-22 November 1972.

8. L. E. Steele, "Initial Results of Studies on the Effects of Cyclotron Implanted Helium on Fatigue Characteristics of Stainless Steels," Princeton University Short Course on Fusion Power, Princeton, New Jersey, 2 November 1972.

9. F. A. Smidt, Jr., "Effects of Vacancy Trapping by Solute Elements on Void Nucleation in Irradiated Metals," Nuclear Engineering Department, Massachusetts Institute of Technology, Cambridge, Massachusetts, 16 January 1973.

10. J. A. Sprague, "The Effect of Beam Scanning on Elevated-Temperature Heavy Ion Damage," Nuclear Engineering Department, Massachusetts Institute of Technology, 16 January 1973.

11. D. J. Michel, "Defect Trapping in Nb-1Zr Alloy," Nuclear Engineering Department, Massachusetts Institute of Technology, 16 January 1973.

12. A. G. Pieper, "Measurement of Helium Depth Profiles in Metal Foils," Amer. Phys. Soc., Washington, D. C., 23-26 April 1973; Bull. Am. Phys. Soc. II, 18: 578 (1973).

13. I. Manning and G. P. Mueller, "Energy Deposition in Ion Bombardment," Amer. Phys. Soc., New York, New York, 29 January - 1 February 1973; Bull. Am. Phys. Soc. II, 18: 56, 1973.

14. G. P. Mueller, "Heavy Ion Radiation Damage," Amer. Phys. Soc, New York, New York, 29 January - 1 February 1973; Bull. Am. Phys. Soc. II, 18: 13, 1973.

15. C. Z. Serpan, Jr., H. H. Smith, D. J. Michel and A. G. Pieper, "Fatigue Crack Growth in Helium-Implanted Nb-1Zr and Mo-TZM," 1973 TMS Meeting, AIME, 29 May - 1 June 1973.

16. C. Z. Serpan, Jr., D. J. Michel, H. H. Smith and A. G. Pieper (presented by J. A. Sprague). "Microstructural Effects of Implanted Helium on Fatigue of 316 Stainless Steel, "Amer. Nucl. Soc. Annual Meeting, Chicago, Illinois, 10-15 June 1973; Trans. Amer. Nucl. Soc. 16:71, 1973.

17. J. A. Sprague, J. E. Westmoreland, F. A. Smidt, Jr. and P. R. Malmberg, "The Effect of Beam Scanning on Nickel-Ion Damage in Nickel," Amer. Nucl. Soc. Annual Meeting, Chicago, Illinois. 10-15 June 1973; Trans. Amer. Nucl. Soc. 16:70, 1973.

18. F. A. Smidt, Jr., J. A. Sprague, J. E. Westmoreland and P. R. Malmberg, "The Effect of Alloy Additions on Void Nucleation and Growth," Conference on Defects and Defect Clusters in BCC Metals and Their Alloys, National Bureau of Standards, Gaithersburg, Maryland, 14-16 August 1973.

19. J. E. Westmoreland, J. A. Sprague, F. A. Smidt and P. R. Malmberg, "Flux (Dose Rate) Effects for 2.8 MeV ^{58}Ni Irradiations of Pure Ni," International Conference on Applications of Ion Ion Beams to Metals, Albuquerque, New Mexico, 2-4 October 1973, pp. 663-674.

20. D. J. Michel, C. Z. Serpan, Jr., H. H. Smith and A. G. Pieper, "Effect of Cyclotron-Implanted Helium and Microstructure of 316 Stainless Steel at 650°C," Princeton University, Symposium on Engineering Problems of Fusion Research, Princeton, New Jersey, 6-9 November 1973.

21. D. J. Michel, C. Z. Serpan, Jr., H. H. Smith and A. G. Pieper, "Effect of Helium on Fatigue Behavior of the Molybdenum-Base Alloy TZM," Amer. Nucl. Soc. Meeting, San Francisco, California, 11-15 November 1973; Trans. Amer. Nucl. Soc. 17:144, 1973.

22. E. A. Wolicki, "Nuclear and Radiation Techniques Applied to Materials," DDR&E Materials Subelement Apportionment Review, NSRDC, Annapolis, Maryland, 25 April 1974.

23. J. A. Sprague, J. E. Westmoreland, F. A. Smidt, Jr. and P. R. Malmberg, "Void Nucleation and Growth in Nickel Ion Bombardments," The Metallurgical Society, AIME Meeting, 20-21 May 1974.

24. F. A. Smidt, Jr. and A. G. Pieper, "Aggregation of Helium Into Bubbles During Postirradiation Annealing," The Metallurgical Society, AIME Meeting, 20-21 May 1974.

25. F. A. Smidt, Jr. and A. G. Pieper, "Helium Mobility and Bubble Formation in 316 Stainless Steel, Aluminum and Vanadium," ASTM Symposium on Effects of Radiation on Structural Materials, Gatlinburg, Tennessee, 11-13 June 1974; ASTM STP 570, pp. 352-368, February 1976.

26. J. A. Sprague, J. E. Westmoreland, F. A. Smidt, Jr. and P. R. Malmberg, "The Effect of Irradiation Parameters on Nickel-Ion Damage in Nickel," ASTM Symposium on Effects of Radiation on Structural Materials, Gatlinburg, Tennessee, 11-13 June 1974; ASTM STP 570, pp. 505-522, February 1976.

27. J. A. Sprague, "Electron Microscopy of Voids and Bubbles," Workshop on Description of Radiation Damage in Metals Using Electron Microscopy, ASTM Symposium on Effects of Radiation on Structural Materials, Gatlinburg, Tennessee, 11-13 June 1974.

28. C. S. Guenzer and I. Manning, "Calculated Displacement Damage by Neutrons in InSb," IEEE Conference on Nuclear and Space Radiation Effects, Fort Collins, Colorado, 15-18 July 1974. IEEE Trans. Nuclear Science NS-21, No. 6, 26-29 (1974).

29. J. A. Sprague, J. E. Westmoreland, F. A. Smidt, Jr. and P. R. Malmberg, "The Determination of Void Formation Parameters in Metals by Heavy-Ion Irradiation," Symposium on The Physics of Irradiation Produced Voids, AERE, Harwell, England, 9-11 September 1974.

30. J. E. Westmoreland, J. A. Sprague, F. A. Smidt, Jr. and P. R. Malmberg, "Flux Dependence of Void Nucleation and Void Growth in 2.8 MeV Nickel-Ion-Irradiated-Nickel," Symposium on The Physics of Irradiation Produced Voids, AERE, Harwell, England, 9-11 September 1974.

31. I Manning and G. P. Mueller, "Approximate Calculation of Energy Deposition in Ion Bombardment," Symposium on The Physics of Irradiation Produced Voids, AERE, Harwell, England, 9-11 September 1974.

32. J. A. Sprague, "Void Formation in Nickel-Ion Irradiated Nickel," Max-Planck Institut fur Metallforschung, Stuttgart, Germany, 16 September 1974.

33. J. E. Westmoreland, "Production of Voids in Metals," Max Planck Institut fur Physik, Munich, Germany, September 1974.

34. J. E. Westmoreland, "Void Formation in Metals by Heavy Ion Bombardment," California Institute of Technology, Pasadena, California, September 1974.

35. J. E. Westmoreland, J. A. Sprague, F. A. Smidt, Jr. and P. R. Malmberg, "Flux Dependence of Void Nucleation and Void Growth in 2.8 MeV Nickel-Ion-Irradiated Nickel," 21st National Vacuum Symposium, Anaheim, California, September 1974.

36. F. A. Smidt, Jr., "Review of NRL Program on Use of Simulation Techniques to Study Radiation Damage in Metals," CTR Workshop on Ion Damage in BCC Metals, Seattle, Washington, 7-8 October 1974.

37. F. A. Smidt, Jr., "Metals in High Temperature Nuclear Environments," ONR Workshop on Light Weight Nuclear Power Plants, Arlington, Virginia, 22-24 October 1974.

38. J. E. Westmoreland, J. A. Sprague, F. A. Smidt, Jr. and P. R. Malmberg, "Dose Rate Dependence of Irradiation Parameters in Nickel-Ion-Irradiated Nickel," Amer. Nucl. Soc. Meeting, Washington, D. C., 27-31 October 1974; Trans. Amer. Nucl. Soc. 19:149, 1974.

39. A. G. Pieper, L. S. August and F. A. Smidt, Jr., "Nondestructive Measurements of Helium Concentration in Metal Foils," Amer. Nucl. Soc. Meeting, Washington, D. C., 27-31 October 1974; Trans. Amer. Nucl. Soc. 19:25, 1974.

40. J. B. Langworthy, M. Rosen, F. H. Attix, S. G. Gorbics and S. M. Seltzer, "Enhanced Dose from Low Energy Bremsstrahlung Following High/Low-Z Interfaces," Amer. Nucl. Soc. Meeting, Washington, D. C., 27-31 October 1974; Trans. Amer. Nucl. Soc. 19:453 (1974).

41. J. A. Sprague, "Void Formation in Nickel-Ion-Irradiated Nickel," Argonne National Laboratory, 6 December 1974.

42. P. L. Hendrick, "Ion-Simulated Irradiation-Induced Creep," Department of Nuclear Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, 4 December 1974.

43. F. A. Smidt, Jr., "The Influence of Minor Alloy Additions on Swelling," Conference on Irradiation Behavior of Fuel Cladding and Core Component Materials, Kernforschungszentrum, Karlsruhe, Germany, 3-5 December 1974.

44. F. A. Smidt, Jr., "Void Formation in Nickel-Ion Irradiated Nickel," Conference on Irradiation Behavior of Fuel Cladding and Core Component Materials, Kernforschungszentrum, Karlsruhe, Germany, 3-5 December 1974.

45. D. J. Michel, "Ion-Simulated Irradiation-Induced Creep," Seminar, Department of Materials Science and Metallurgical Engineering, University of Cincinnati, Ohio, 6 May 1975.

46. F. A. Smidt, Jr. and A. G. Pieper, "Observations of Helium Bubble Formation in 316 Stainless Steel Implanted by Alpha-Bombardment," International Conference on Radiation Effects and Tritium Technology for Fusion Reactors, Gatlinburg, Tennessee, 1-3 October 1975; CONF-750989, Vol. II, pp. 250-279, March 1976.

47. J. A. Sprague, "The Evaluation of Time Dependent Void Nucleation Under Ion-Bombardment Conditions," International Conference on Fundamental Aspects of Radiation Damage in Metals, Gatlinburg, Tennessee, 6-10 October 1975. Proceedings: pp. 1181-1187, Washington: U. S. Government Printing Office 1976.

48. P. L. Hendrick, D. J. Michel, A. G. Pieper and R. A. Surratt, "Irradiation Induced Creep of Nickel," International Conference on Radiation Effects and Tritium Technology for Fusion Reactors, Gatlinburg, Tennessee, 1-3 October 1975; CONF-750989, Vol. II, pp. 84-117, March 1976.

49. F. A. Smidt, Jr., "Factors Influencing Swelling in Metals Bombarded with Heavy Ions," Seminar, University of Virginia, Charlottesville, Virginia, 3 December 1975.

50. P. L. Hendrick, "Ion-Simulated Irradiation-Induced Creep of Nickel," Seminar, Physics Department, Georgetown University, Washington, D. C., 5 December 1975.

51. J. A. Sprague, F. A. Smidt, Jr., J. E. Westmoreland and P. R. Malmberg, "The Effect of Ion Irradiation on the Microstructure of an Fe-Ni-Cr Alloy," ASTM Symposium on the Effects of Radiation on Structural Materials, St. Louis, Missouri, 2-5 May 1976; ASTM-STP 611, pp. 337-352 (1976).

52. D. J. Michel, P. L. Hendrick and A. G. Pieper, "Microstructure and Mechanisms of Ion-Simulated Irradiation-Creep of Nickel," ASTM Symposium on the Effects of Radiation on Structural Materials, St. Louis, Missouri, 2-5 May 1976; ASTM STP 611, pp. 284-297 (1976).

53. L. G. Kirchner, F. A. Smidt, Jr. and J. A. Sprague, "Nickel Ion Damage in a Precipitation Hardened Ni-Al Alloy," ASTM Symposium on the Effects of Radiation Structural Materials, St. Louis, Missouri, 2-5 May 1976; ASTM STP 611, pp. 370-384 (1976).

54. F. A. Smidt, Jr., "The Use of Microstructure Evolution as an Aid in Correlating Ion and Neutron Data, and Questions Concerning the Introduction of He in Charged Particle Simulation Experiments," Workshop on Correlation of Neutron and Charged Particle Damage, Oak Ridge, Tennessee, 8-10 June 1976; (CONF-760672-2) (HEDL-SA-874), Springfield, Virginia: NTIS.

55. J. E. Westmoreland, P. R. Malmberg, J. A. Sprague, F. A. Smidt, Jr. and L. G. Kirchner, "Dose Rate Effects in a Precipitation-Hardened Nickel-Aluminum Alloy," International Conference on Ion Implantation in Semiconductors and Other Materials, Boulder, Colorado, 8-13 August 1976; (CONF-760836-5), Springfield, Virginia: NTIS.

56. D. J. Michel, P. L. Hendricks and A. G. Pieper, "Transient Ion Simulated Irradiation Induced Creep of Nickel," American Nuclear Society Meeting, New York, New York, 12-16 June 1977; Trans. Amer. Nucl. Soc. 26:195, 1977.

57. W. G. Wolfer, L. K. Mansur and J. A. Sprague, "Theory of Swelling and Irradiation Creep," AIME International Conference: Radiation Effects in Breeder Reactor Structural Materials, Scottsdale, Arizona, 19-23 June 1977; (CONF-770641-7), Springfield, Virginia: NTIS.

58. J. A. Sprague, "Void and Bubble Size Measurement: The Effect of Focus Condition," 35th Meeting of Electron Microscopy Society of America, Boston, Massachusetts, 22-26 August 1977.

59. F. A. Smidt, Jr., J. R. Reed and J. A. Sprague, "A Comparison of the Swelling Produced in Nickel by Neutron Irradiation and Ion Irradiation," AIME International Conference: Radiation Effects in Breeder Reactor Structural Materials, Scottsdale, Arizona, 19-23 June 1977; (CONF-770641-7), Springfield, Virginia: NTIS.

☆ U. S. GOVERNMENT PRINTING OFFICE : 1979 281-484/115